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Sharp Technologies as Applied to a Crew Transfer Vehicle (CTV)

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April 10, 2003

NASA Entry Vehicles and Missions Supported by Ames

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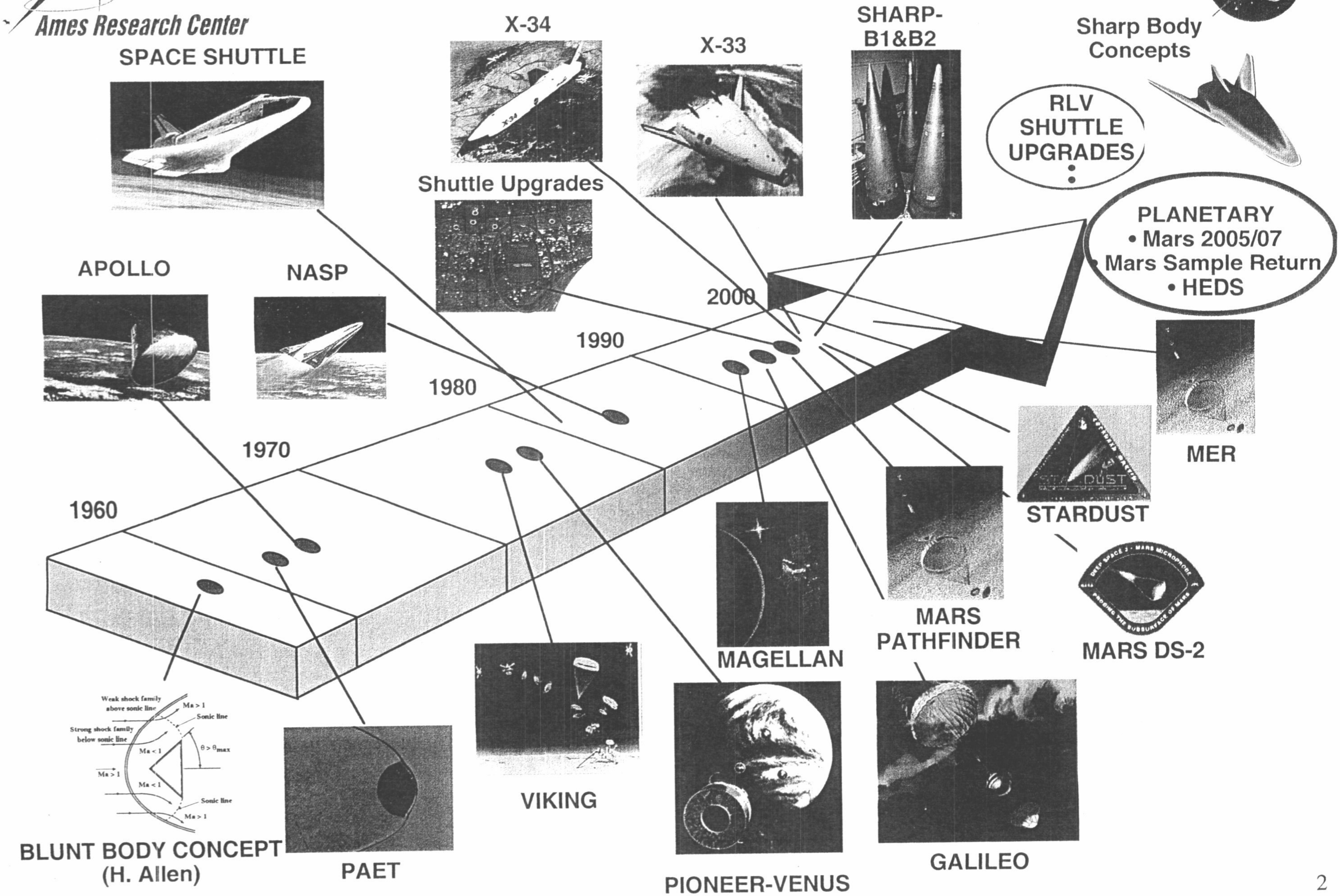
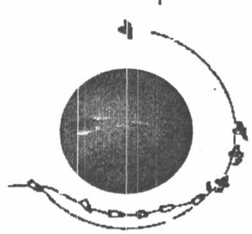


Sharp Technology Impacts

- Enabled by Ultra-High Temperature Ceramics (UHTC's)
  - Temperature capability of 4000-5000°F, in contrast to the ~3000°F max limit for Shuttle
- Allows sharp leading edges for hypersonic vehicles
  - Tenths to hundredths of an inch radii, as opposed to Shuttle with radii measured in feet
- Enables sharp body vehicle concepts with low drag
  - Critical for airbreathing propulsion, rail launchers, and aero-maneuvering vehicle concepts, providing significantly reduced costs
- Allows high lift hypersonic vehicle designs
  - Providing aircraft-like maneuverability, including landings at standard airports, and enabling global cross range for greatly improved safety
- Eliminates entry communications blackout
  - Enhances GPS navigation with continuous communications, further improving safety and reliability
- Enables future safe, affordable aerospace vehicles

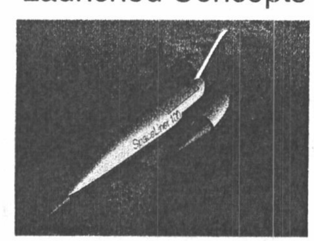
Aero-Maneuvering Concepts



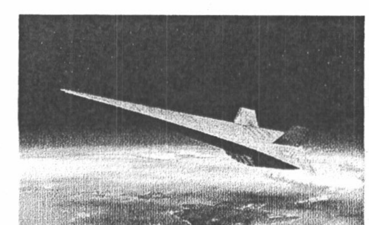
Commercial Global Express

New Reusable Launch Vehicles

RBCC and Rail Launched Concepts



Future DoD Vehicles

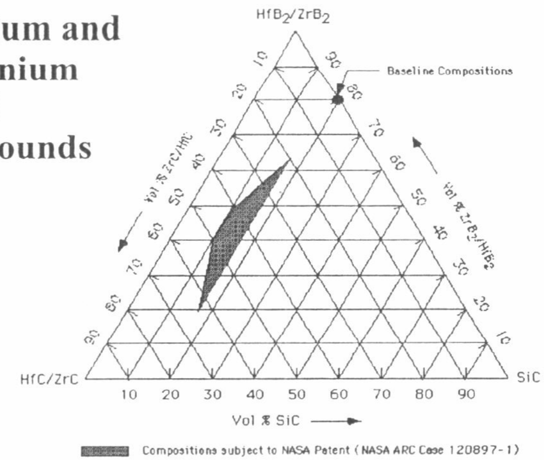


Ultra-High Temperature Ceramics (UHTC's)

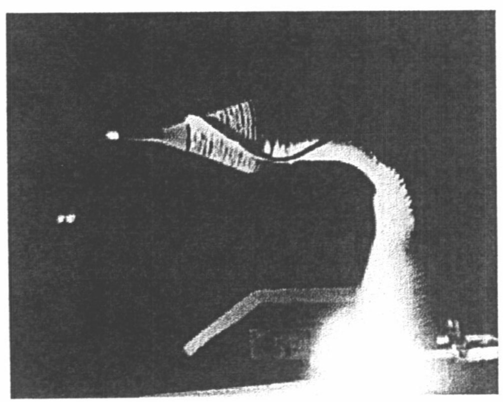
UHTC's have a unique combination of thermal and mechanical properties that enable their operation from room to *ultra-high* temperatures, including:

- **Base material melt temperatures up to 7000°F**
- **Oxide melt temperatures up to 5000°F**
- **Flexural strengths up to 720 MPa**
- **Thermal Conductivities up to 104 W/m-K**
- **Thermal Expansion Coef as low as 4.2 ppm/K**
- **Moduli as low as 214 GPa**

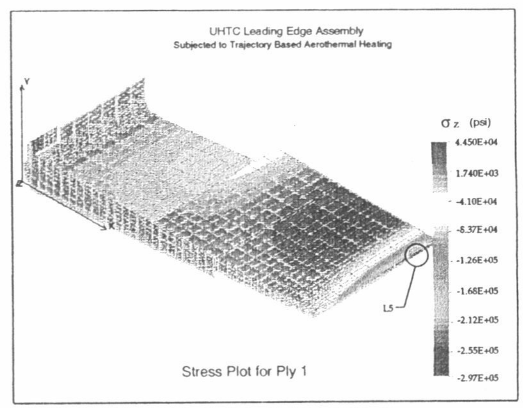
Hafnium and Zirconium based compounds



UHTC's form a surface oxidative and thermal barrier in-situ, providing fail-safe operation



UHTC sharp leading edges can be designed to sustain in-flight thermal and aerodynamic loads



SHARP* Program Completed to Date

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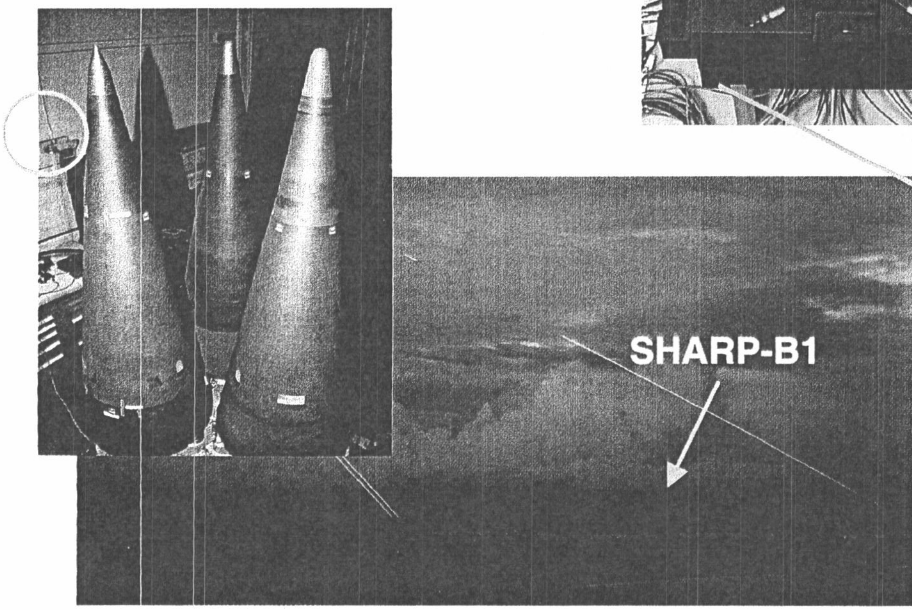
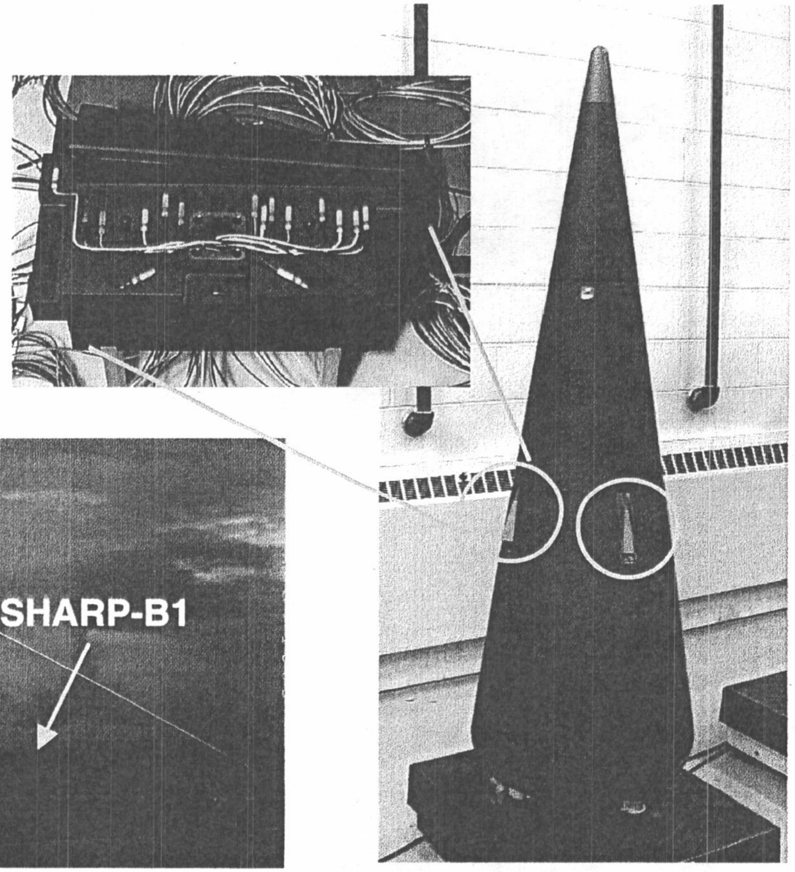


SHARP-B1: Successfully completed in 6 months (May 1997 flight)
Objective: Verify UHTC sharp nosetip thermophysical performance
Team: NASA ARC, Sandia, USAF, White Materials, Paul Beckman Corp.



SHARP-B2: Successfully completed and flow in 21 months (Sept. 2000 flight)
Objective: Verify UHTC sharp leading edge thermostructural performance
Team: NASA ARC, MSFC, Sandia, SoRI, USAF, Materials and Machines, Paul Beckman Corp.

Sandia's involvement and contributions, and the support of the Air Force, have been key to the success of the SHARP program to date

Sandia National Laboratories

***<u>S</u>lender <u>H</u>ypersonic <u>A</u>erothermodynamic <u>R</u>esearch <u>P</u>robes**

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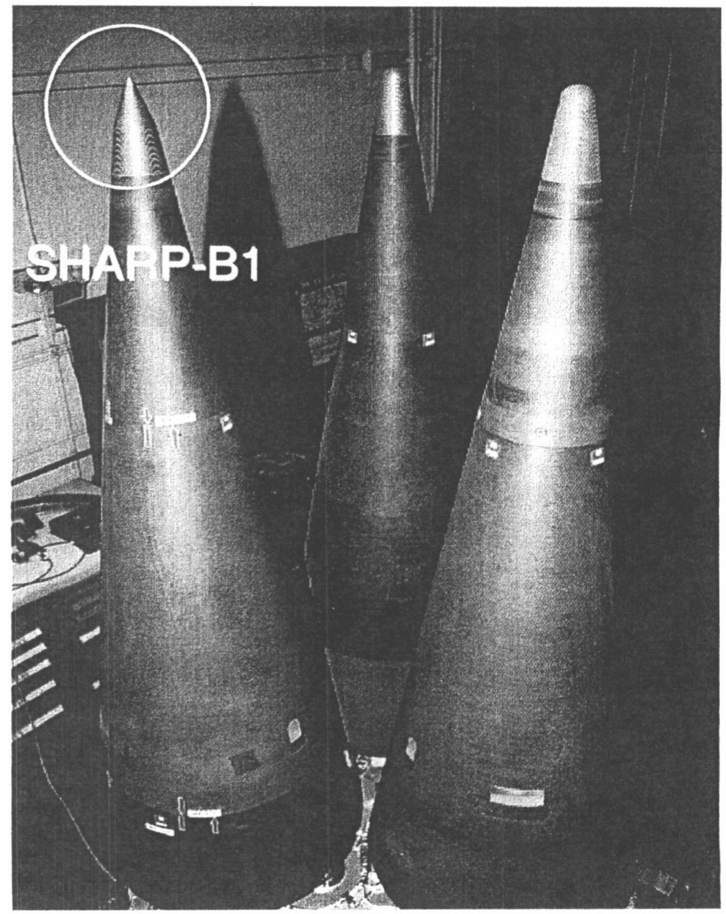
SHARP-B1: May 21, 1997

- UHTC first flight demonstration
  - Funded 1/97, flew 5/97!
  - NASA Cost $1.2 M
  - Designed, built, tested, & flew .141” radius UHTC nosetip
  - Partnered with Sandia National Labs, USAF
  - Minuteman III launch
  - Instrumented UHTC nosetip on modified reentry vehicle
  - Design passed rigorous qualification testing and flight



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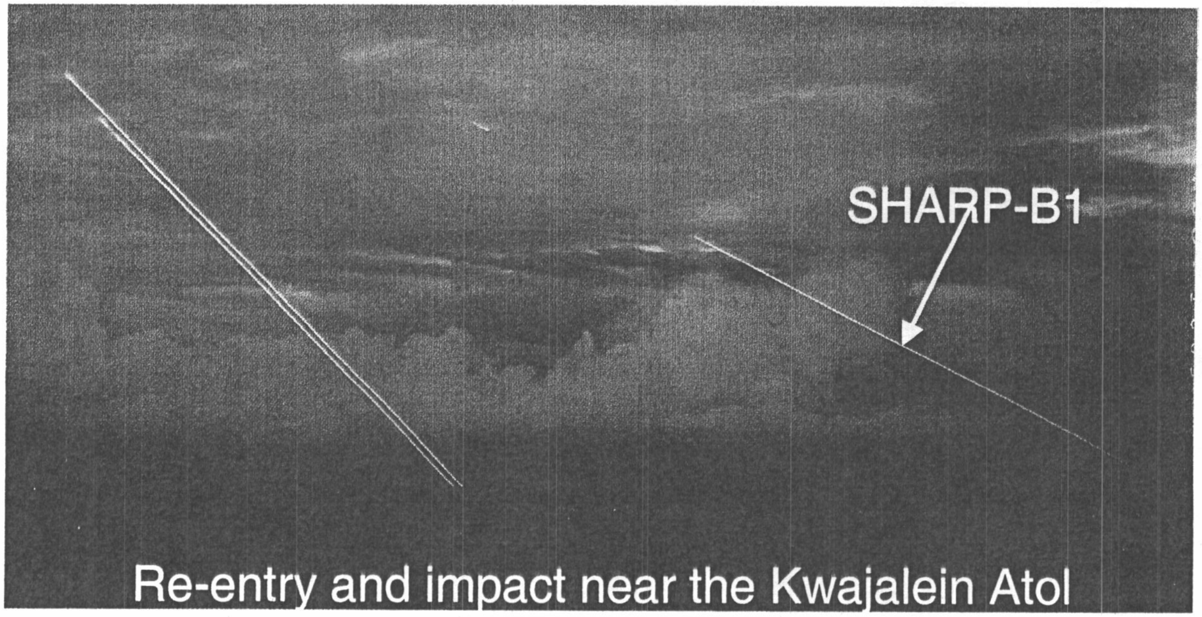
SHARP-B1 Flight Results Summary



- Nosetip Material met/exceeded expectations
  - Ablation occurred after crossing aerothermal performance constraint, surface temps of +5000° F generated
  - No communication blackout, normal RF attenuation was reduced.

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SHARP-B1 Post-Flight Results & Recommendations

- Steady state analysis giving UHTC nosetip ablation limit corresponds well with measured flight performance, showing apparent UHTC ablation onset
- Discrepancy between predicted and measured transient nosetip temperatures not understood and requires further study
- Recommendations for further study:
  - Simulate the transient response of the SHARP-B1 nosetip at high altitude by DSMC/COSMOS.
  - Use this simulation for improving the rarefied flow correlations in PERFORM/COSMOS and reduce the discrepancy between the transient analysis and the flight data.
  - Perform a frequency analysis of the signal output between Event 2 and Event 3.
  - Use this analysis for correlating the output of the Tier 1 thermocouples to the Mk12A vehicle dynamics.
- Additional flight test, including recovery of UHTC components, should be pursued

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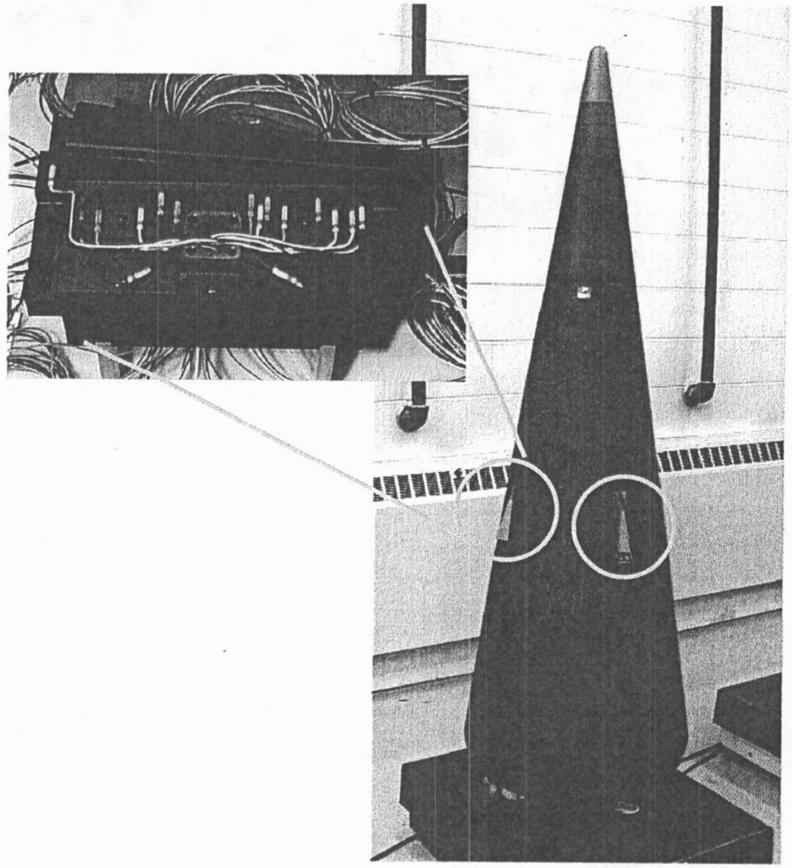
SHARP-B2 Launch & Recovery Highlights

- Launched September 28, 2000 3:01 a.m. from VAFB.
- Tracked with 3 radar systems.
- Full retraction on strake #4 took longer than expected.
- Main chute malfunction caused vehicle to impact nearly 3X faster than expected, but minimal damage to strakes.
- 100% data collection on 140 channels.
- Vehicle recovered from a depth of 165 feet, approximately 500 feet from predicted impact point on October 1, 2000.



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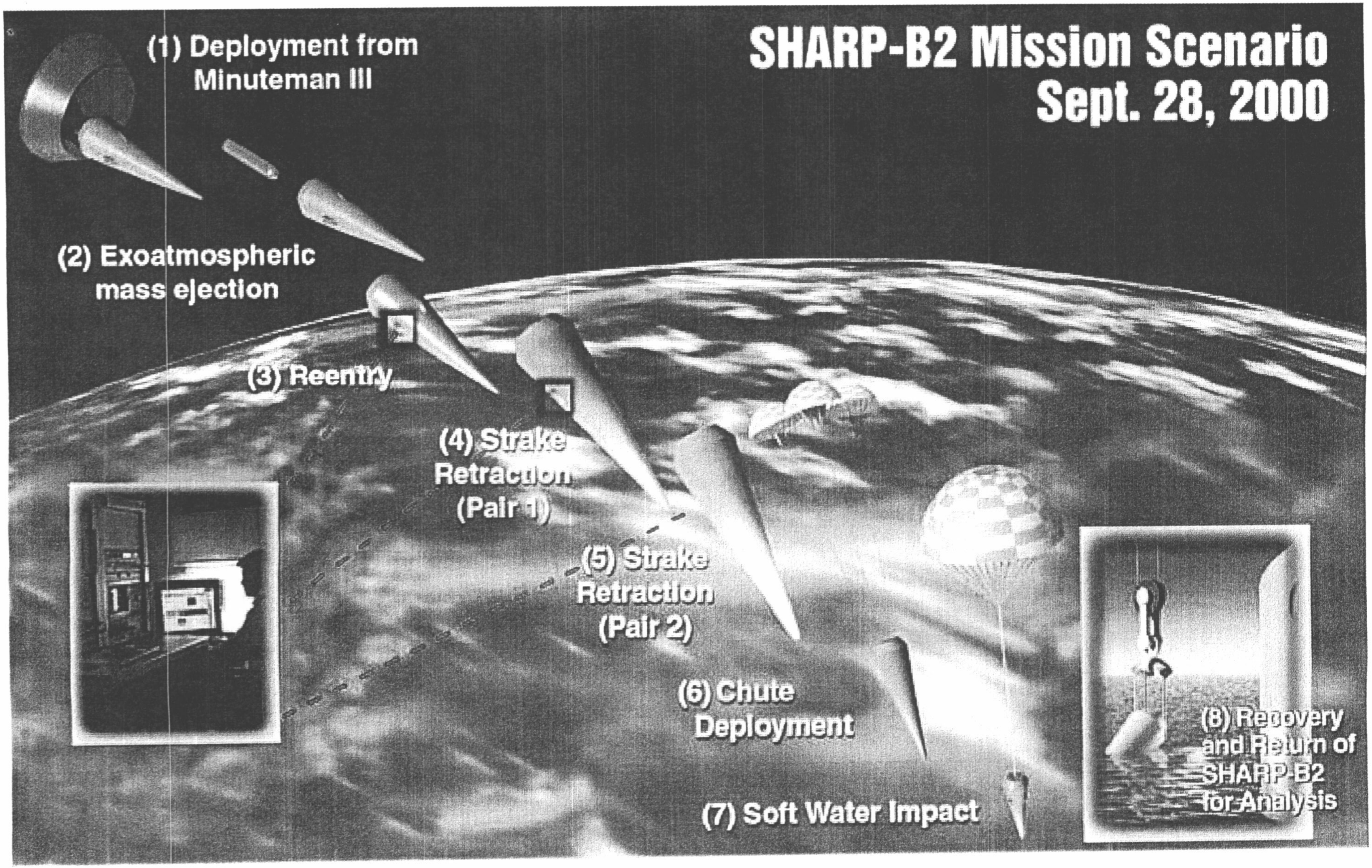
SHARP-B2 Mission Scenario
Sept. 28, 2000
(1) Deployment from Minuteman III
(2) Exoatmospheric mass ejection
(3) Reentry
(4) Strake Retraction (Pair 1)
(5) Strake Retraction (Pair 2)
(6) Chute Deployment
(7) Soft Water Impact
(8) Recovery and Return of SHARP-B2 for Analysis

SHARP-B2 Strake Response Highlights

- Recorded material temperatures were significantly below predictions
  - Similar low measured temperatures occurred with B1
  - Boundary layer/rarified flow/instrumentation effects being investigated to determine cause
- Thermal structural fractures occurred in the strakes in flight:
  - All four HfB2/SiC strake segments encountered multiple fractures
  - Two of the four ZrB2/SiC strake segments encountered fractures
  - None of the four ZrB2/SiC/C segments fractured
- High defects levels in the materials (particularly for the HfB2/SiC strake segments) believed to have at least contributed to the fracturing

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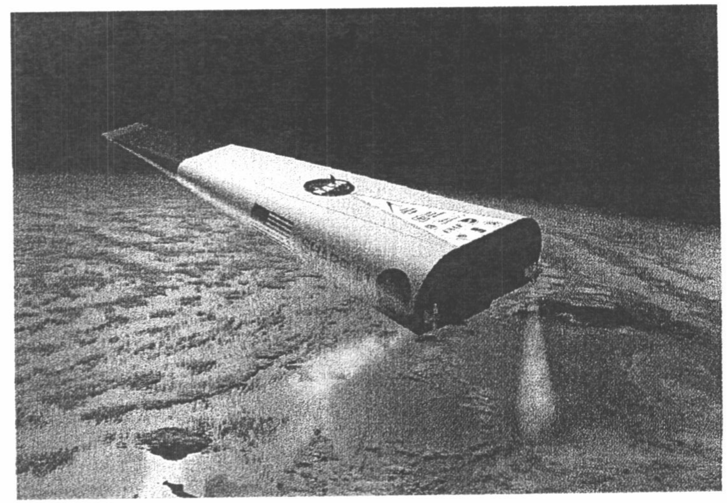
SHARP Program Yet to Be Accomplished/Funded

- SHARP-L1
  - Demonstrate key technologies for operable sharp body vehicles:
    - Sharp UHTC leading edge assembly & acreage TPS
    - Novel lifting vehicle design and flight control
    - Landing/recovery systems
  - Schedule: 36 months from authority to proceed
  - Team members: ARC, Sandia, Air Force, Industry



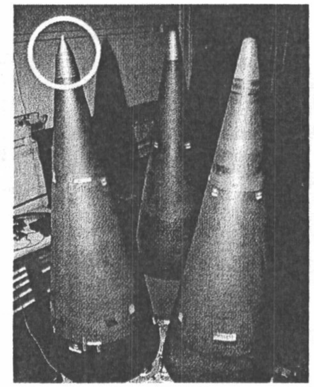
- *Flight Scenario*
  - *Launched off of a Pegasus-XL, or other available boost asset*
  - *Mach 23+ re-entry*
  - *Flight into the Western Pacific Missile Test Range*
  - *Mid-air, intact recovery (Johnston Island recovery one option)*

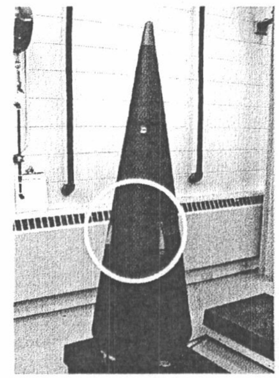
Summary of SHARP Program

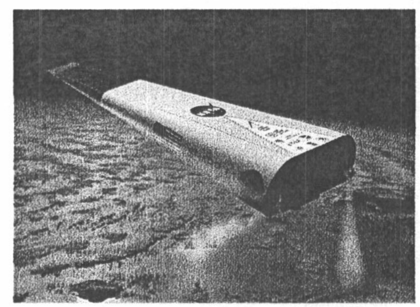
- SHARP-B1
  - Funded ($1.2M) from discretionary reserves at the direction of HQ, Code R (Col. Gary Payton)
  - Successfully flew on May 21, 1997, six months after authority to proceed

- SHARP-B2
  - Awarded (~$6M) under the first cycle of the MSFC Future-X program
  - Designed, fabricated, completed systems testing on budget and schedule (18 months), and successfully launched and recovered in September, 2001

- SHARP-L1
  - Initial development study completed under Spaceliner 100 program (~$2M)
  - Estimated program for flight hardware design, fabrication and flight testing ~$50M
  - Currently working continued UHTC ground development (have brought materials fabrication capability in-house), and sharp body systems studies under NASA 2nd Gen (SLI) and 3rd Gen (ASTP) RLV development programs







Ames SHARP CTV Architecture Study Plan

Products

- Vehicle Concepts and Analysis (Include Performance, Mass, Trajectory, Reusability, Safety)
- Identify Key Trades and Sensitivities
  - L/D and cross-range/aborts
  - Subsonic landing and handling qualities
  - Vehicle mass/scale
  - SHARP/UHTC trades
- Mature RLV Analysis and Design Capabilities for 2nd Gen.
- Documentation of Study Results

Schedule

- 9-Month Study, Finished October 2000.

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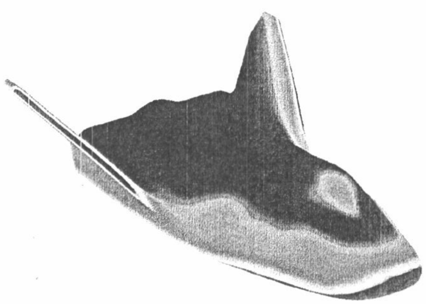
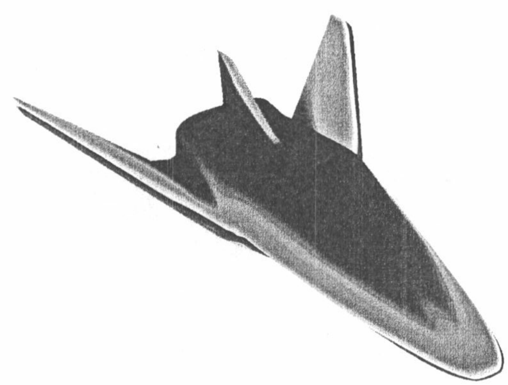
NASA Ames CTV Mission Studies

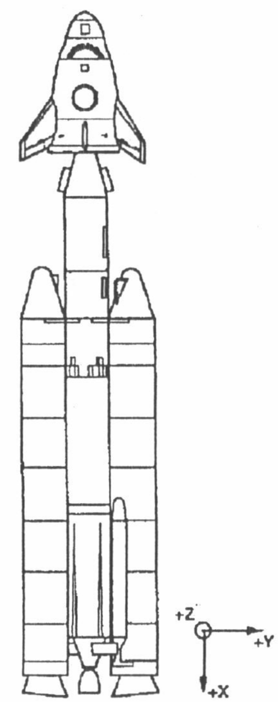
- Enter Orbit from Atop an Expendable Launch Vehicle
- Carry 8 Crew and 2 Pilots with Full Life Support for Multiple Days in Orbit
- Dock with International Space Station (ISS) for Crew Transfer
- Return from Orbit and Land on a Hardened Runway
- Survive a Range of Intact Ascent Aborts
- Fully Reusable TPS and Complete Vehicle Systems



HL-20



SHARP-V5

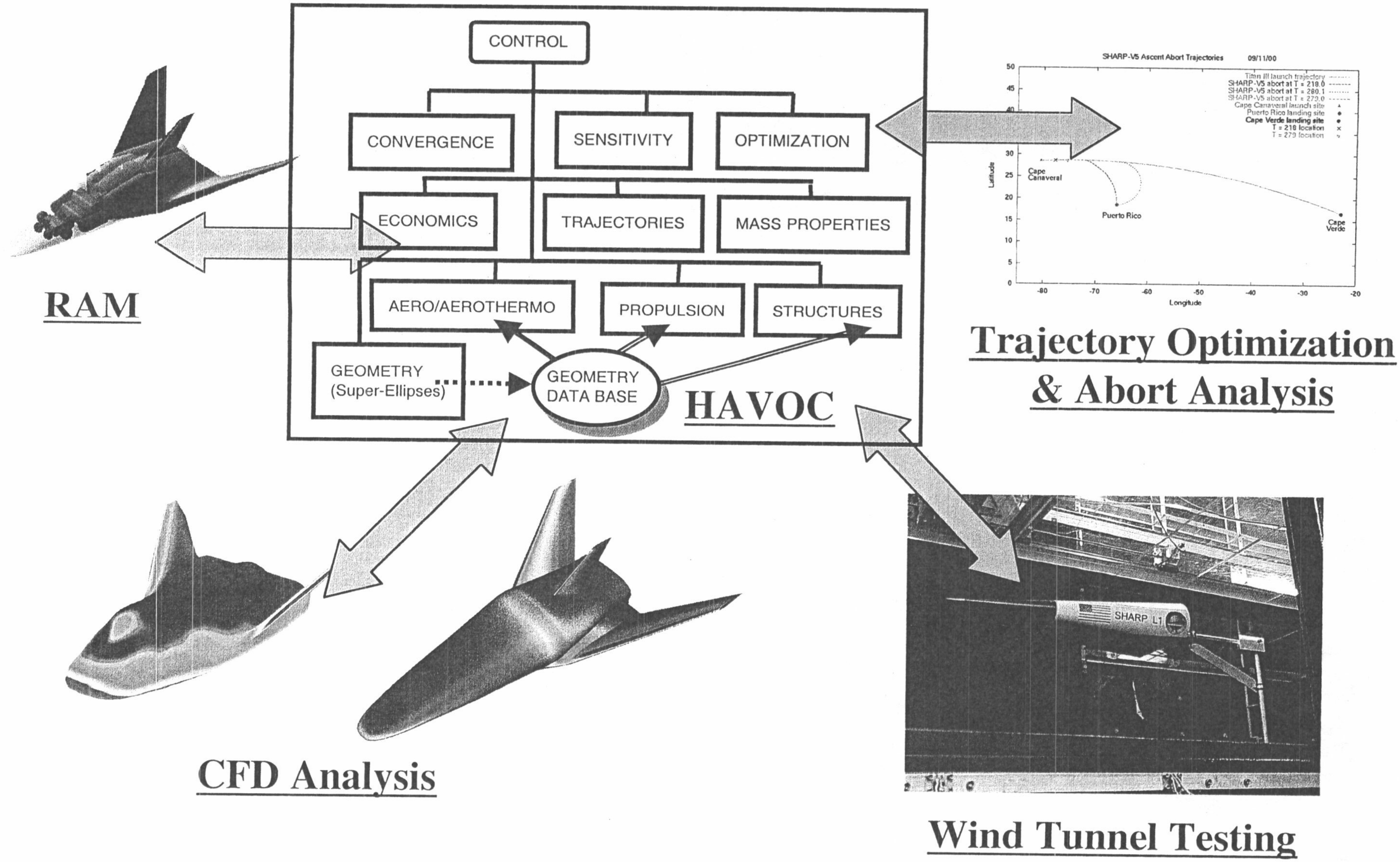


HL-20 Ascent Stack

HL-20 Chosen for Tools Validation

- **HL-20 Studied at NASA LaRC in Late 80s and Early 90s**
  - Multi-year, dedicated division effort
- **Extensive Results Published, Notably a Dedicated JSR Volume (1993)**
- **Rationale for Using HL-20**
  - Study results are recent, well documented, and fairly complete
  - Similar "CTV" design requirements
- **Use of HL-20 Results by Ames CTV Team**
  - As tool validation resource with comprehensive data
  - As solid comparison vehicle designed without SHARP technologies

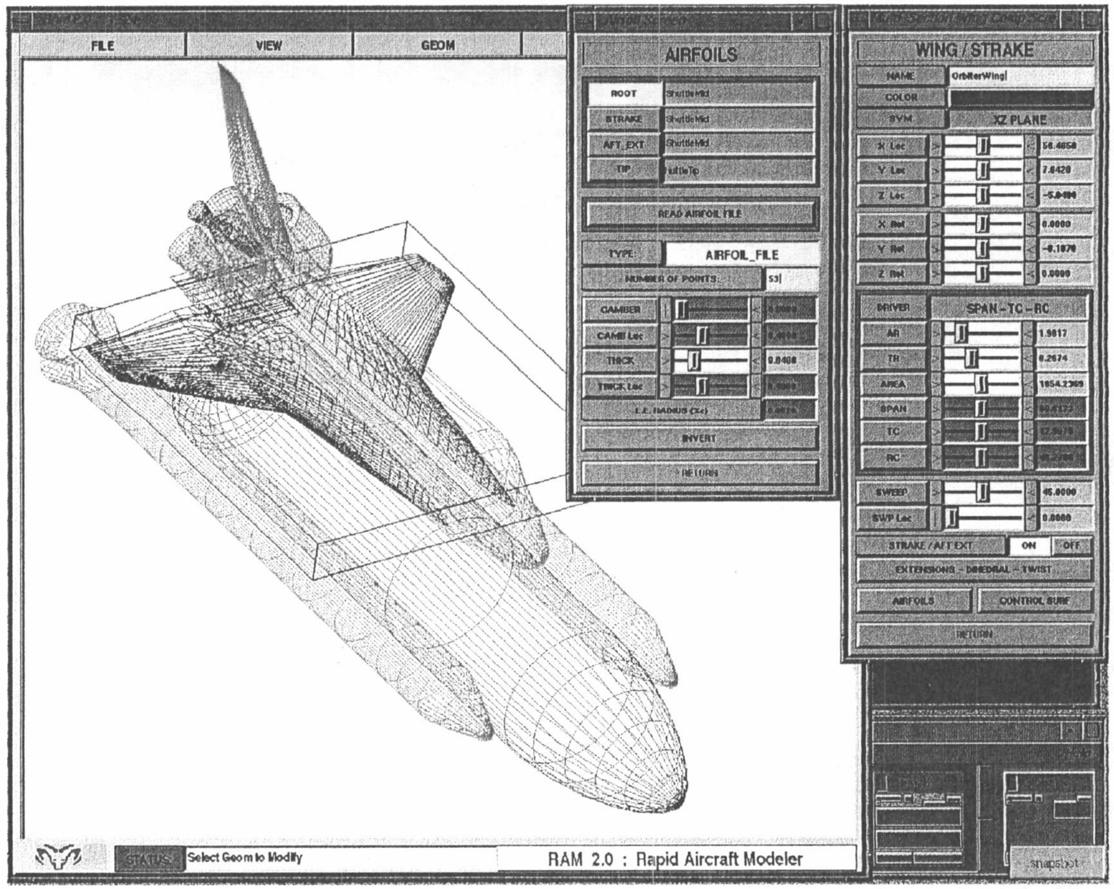
Vehicle Sizing and Closure Process



HAVOC Design Methodology

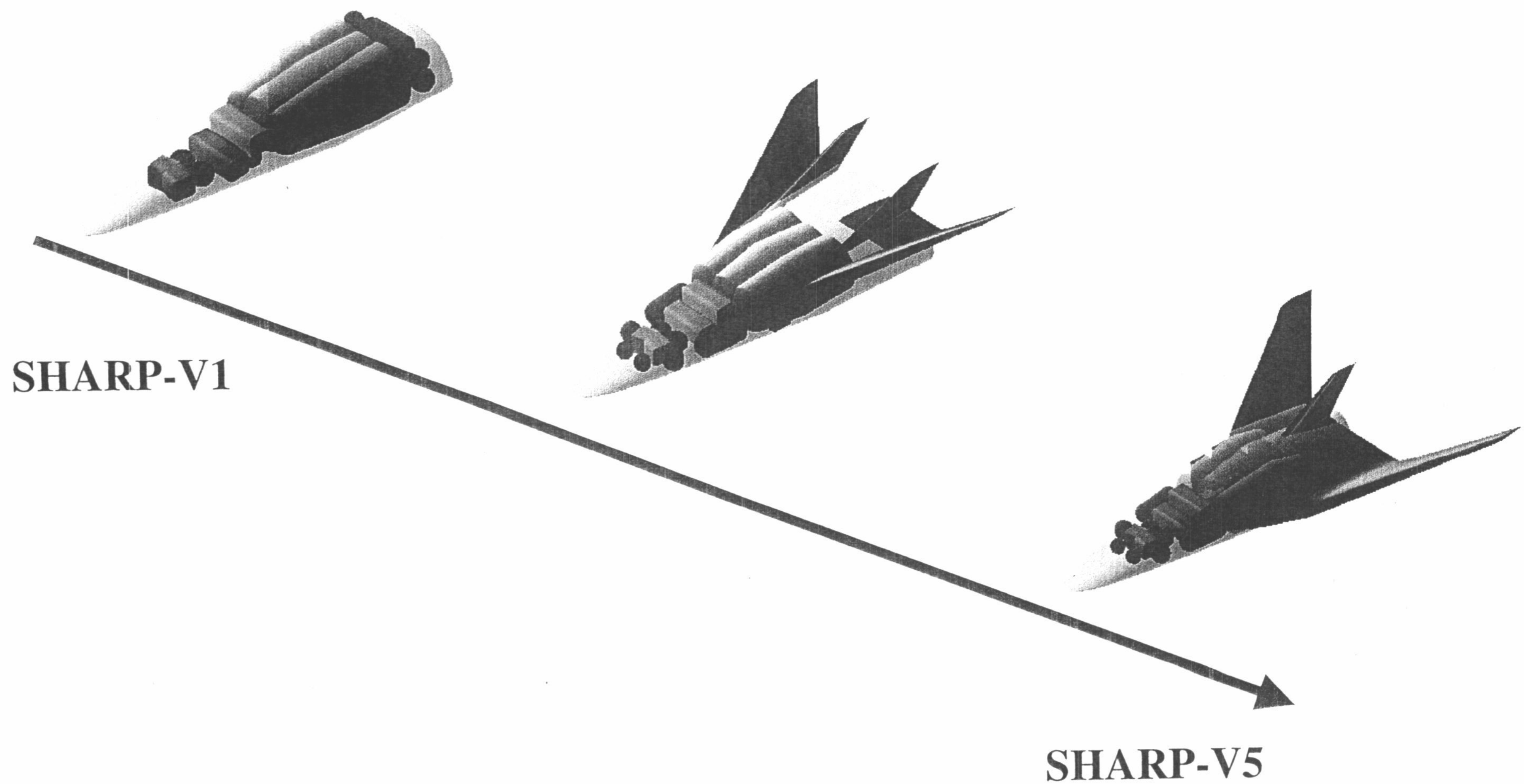
- **Approach uses conceptual level spacecraft systems analysis and synthesis code HAVOC (Hypersonic Air Vehicle Optimization Code).**
- **Analysis Sequence includes:**
  - Configuration Layout in RAM
  - HAVOC grid development from RAM layout
  - HAVOC aerodynamic and aerothermal database development, supplemented with low and high speed CFD data, and low speed wind tunnel.
  - Iterative HAVOC runs to establish vehicle closure for mission.

RAM - Rapid Aircraft Modeler

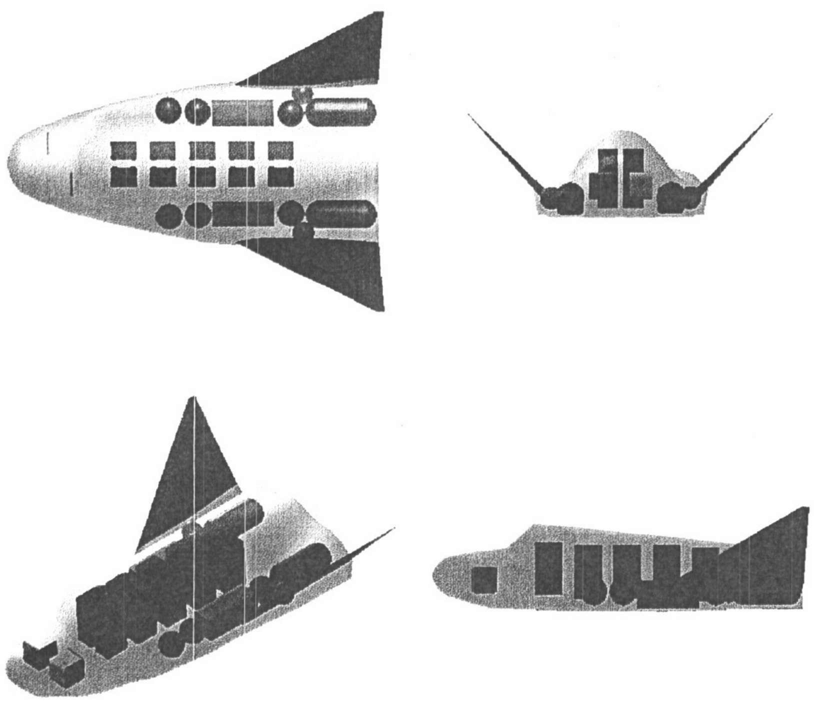


- **Parametric Based**
- **Real Time GUI**
- **Components:**
  - Wings
  - Fuselages
  - Engines
  - Inlets
- **Import Background:**
  - Images
  - Geometries
- **Current Uses**
  - Create and verify geometry for conceptual designs (HAVOC, ACSYNT...)
  - Calculation of wetted areas and volumes
  - Generate geometry for more detailed analysis codes (FLO107-MB, TIGER, GASP...)

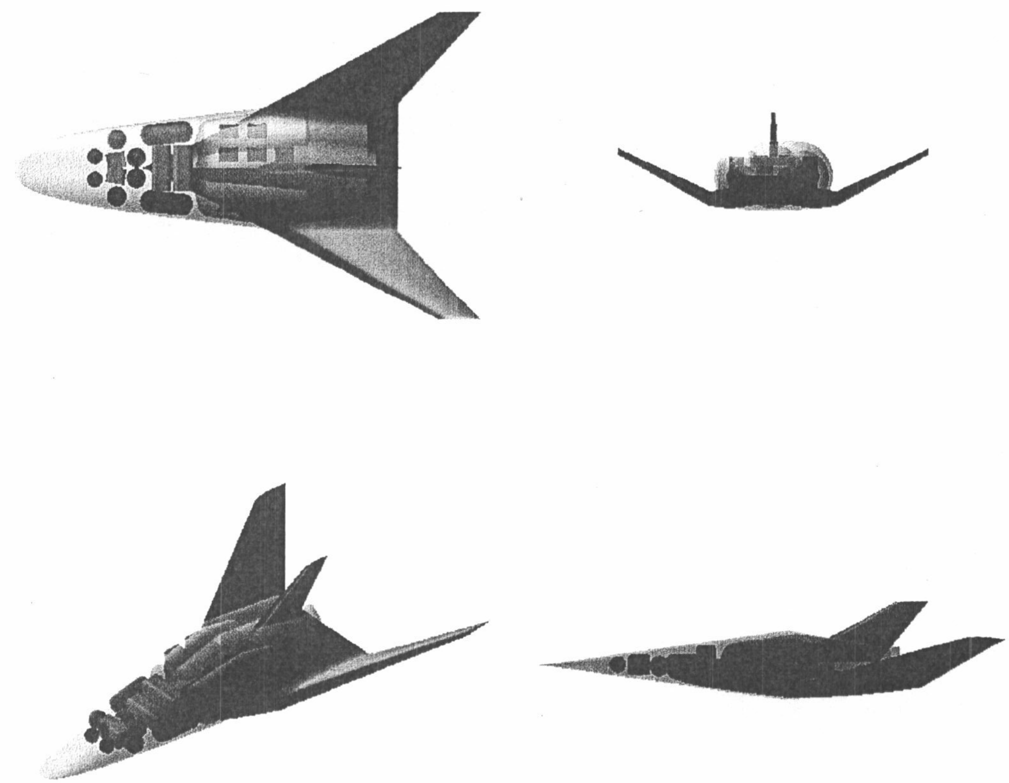
Configuration Development



RAM Models

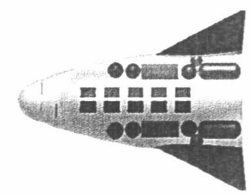


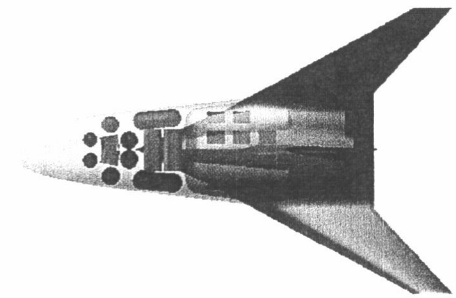
HL-20



SHARP-V5

Configuration Characteristics



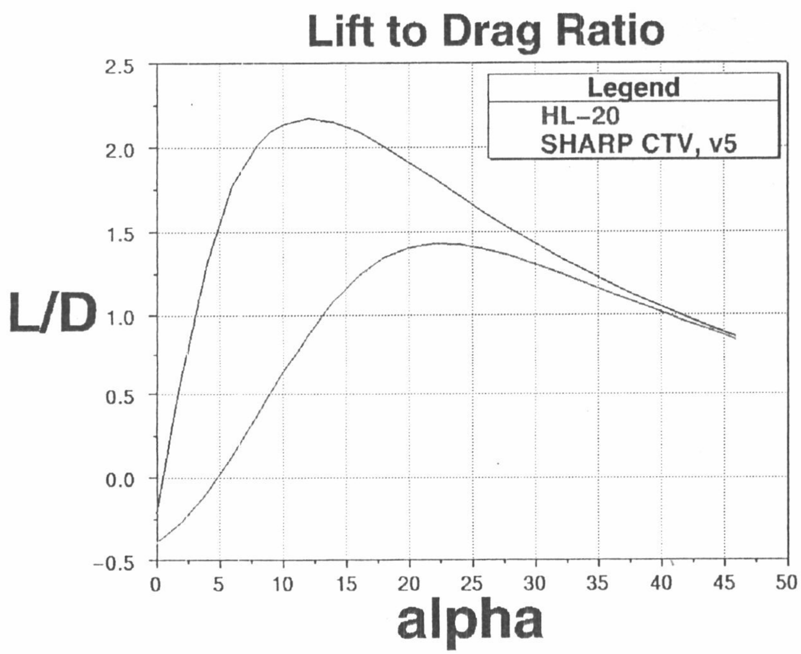


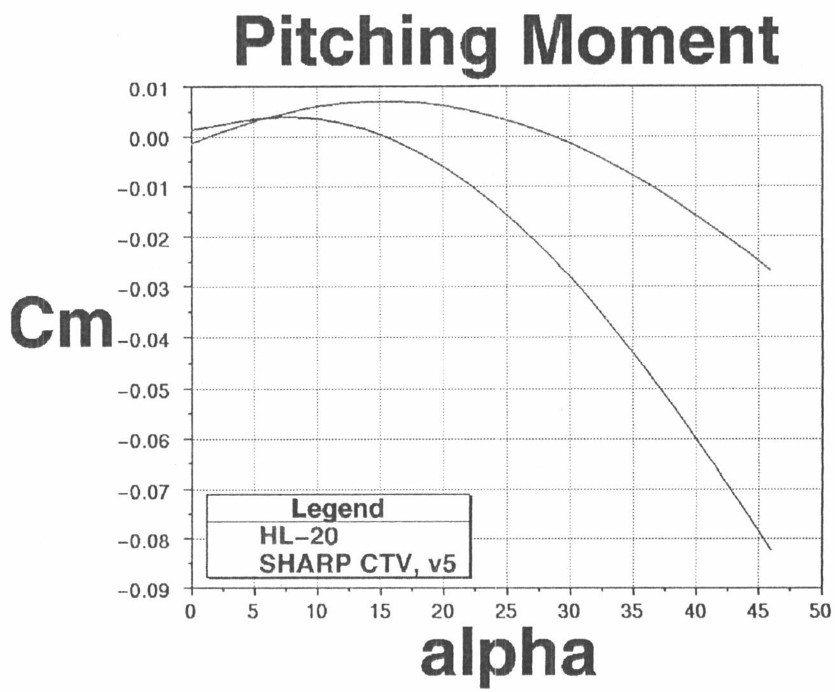
Re-Entry Weight, lbs	24517	25504
Empty Weight, lbs	20021	21000
Airframe Weight	8056	8766
Propulsion	1370	1436
Fixed Equipment	10595	10805
Payload/Crew	3771	3771
Consumables	726	726
Acreage TPS lbs/sqft avg	1.3	1.74*
Body length, ft	28.6	36.6
Wetted Area, sqft	935	1486
Re-entry W/S, psf	66.9	50.1
Re-entry CG	54%	57%
Hypersonic L/D	1.35	2.2

*Preliminary results, body only.

HAVOC Newtonian Aerodynamics

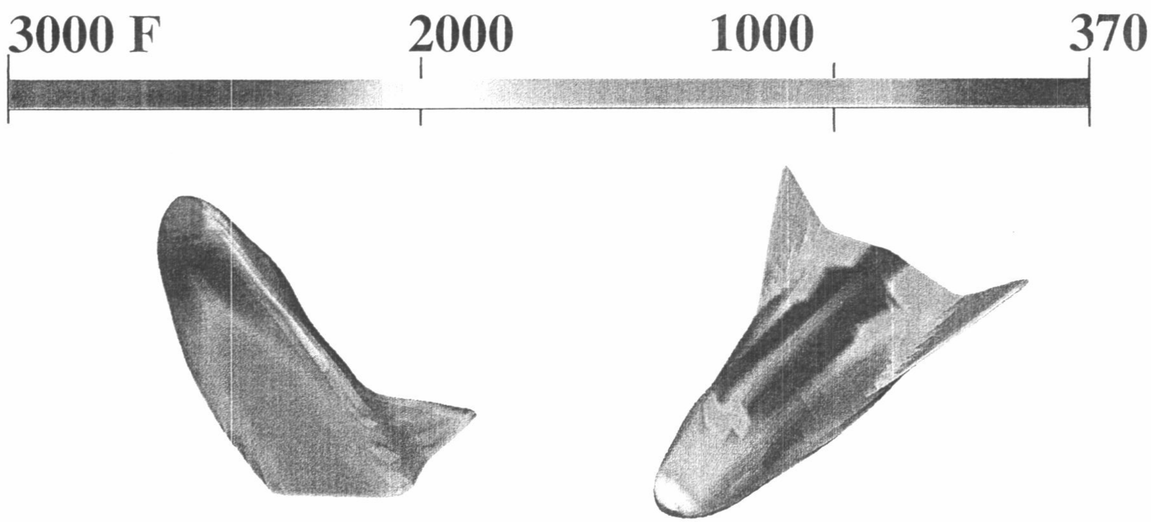
HL-20 and SHARP-V5, Mach 25, Q=10 psf





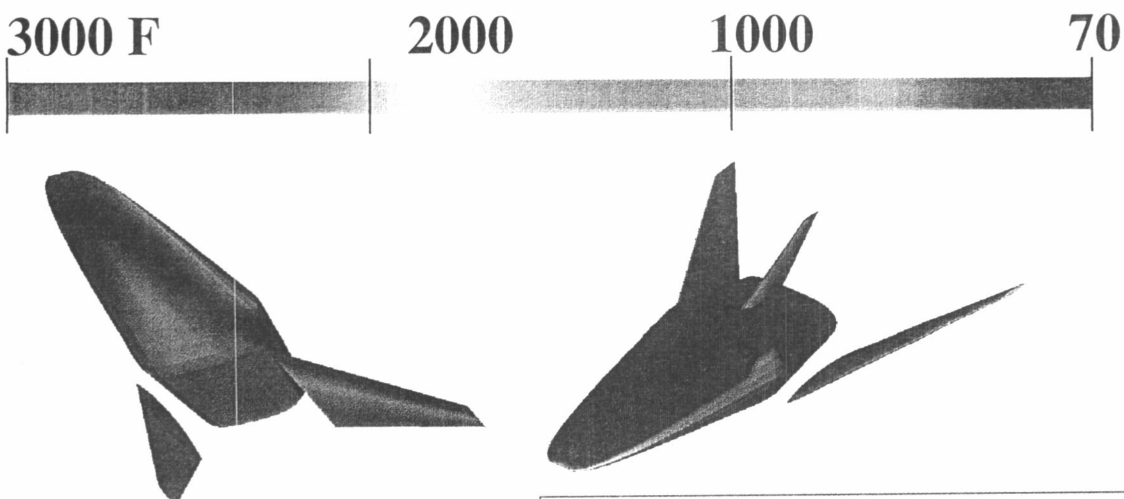
Laminar Peak Heating Points

HAVOC Results



Peak Laminar Heating Point

Mach 25
240 kft
Alpha = 30
Q = 29 psf



Peak Laminar Heating Point

Mach 25
220 kft
Alpha = 12.5
Q = 72 psf

Note: SHARP CTV-v5 results do not include UHTC/ACC nose region.

TPS Sizing

- **TPS sizing based on aerothermal environment**
  - TRAJ optimized trajectory used along with HAVOC aerothermal database
  - 1 D, unsteady analysis of TPS/structural lay up for 2500 body points
  - Convection + Radiation + Wall Conduction are balanced
  - TPS is sized to meet an interior wall temperature constraint (350 F)
- **HL-20 TPS sized and compares well with results presented in JSR 1993**
- **SHARP-V5 TPS sized**
  - Investigated Various TPS Systems
    - All Tile systems vs. Tile and Blanket Systems
    - Acreage TPS choice driven by both temperature and allowable TPS thickness
  - UHTCs Used Only on Sharp Nose Region
    - UHTC and ACC integration and design not completed
    - Aerothermal environment is within APC of UHTC and ACC

SHARP-V5 TPS/Structural Lay Up

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nose, chines, flaps, wing leading edge

- 0.1" ACC
- 6" Gap
- **LI-2200**
- 0.02" RTV
- 0.09" AL-2219

max. temperature 2500 °F

- 0.1" TUFI
- **AETB-12**
- 0.02" RTV
- 0.0625" GP Face Sheet (GP: Graphite Polyimide)
- 0.5" GP Honeycomb
- 0.0625" GP Face Sheet
- 6" Gap
- 1.0" Q-Felt
- 0.02" RTV
- 0.09" AL-2219

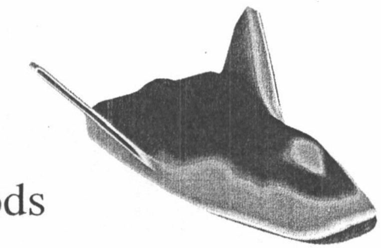
x > 26'

- AFRSI Blanket:
  - 0.027" outer sheet (Astro-Quartz)
  - **Q-felt** (microquartz)
  - 0.011" inner sheet (E-glass)
- 0.02" RTV
- 0.09" AL-2219

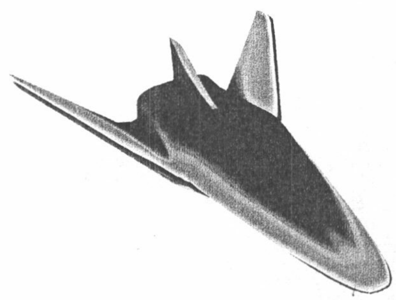
- **UHTCs Used at Nose Tip**
- **Integration with ACC not Completed**

CFD

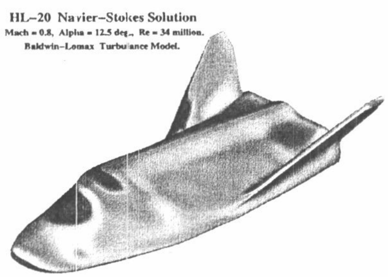
- **GASP for Hypersonic Aero and Heating**
  - Validated against HL-20 published data
  - Provides Anchoring for Engineering Aero and Heating Methods
- **Multi-block/Parallel NS for Low Speed**
  - Validated Against HL-20 Published Data
  - Provides Landing Aerodynamic Database
  - Provides Method of Obtaining Control Effectiveness
  - Fast Turn-Around (~ 15 Minutes per N-S Solution)



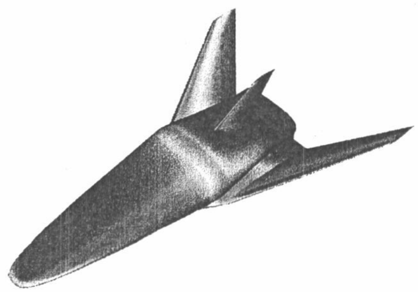
Mach 18 GASP Solution
5 species air
Fully catalytic wall



Mach 23.8 GASP Solution
5 species air
non-catalytic wall



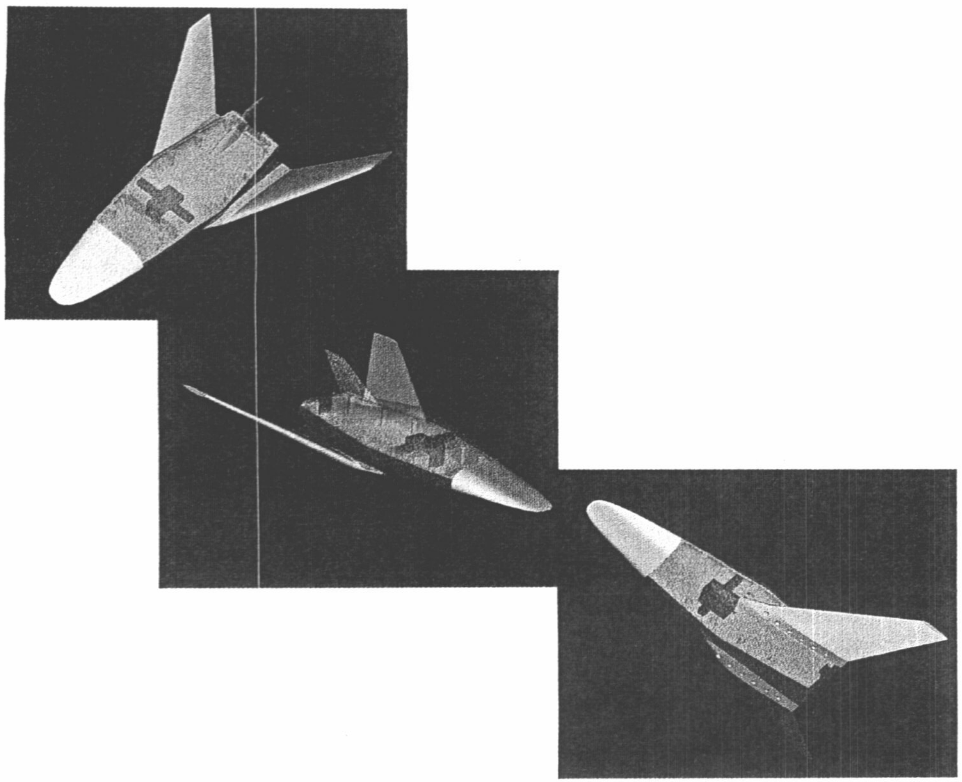
Navier-Stokes Solution
Mach = 0.8, Alpha = 12.5, Re = 34 mil.
Baldwin-Lomax Turbulence Model

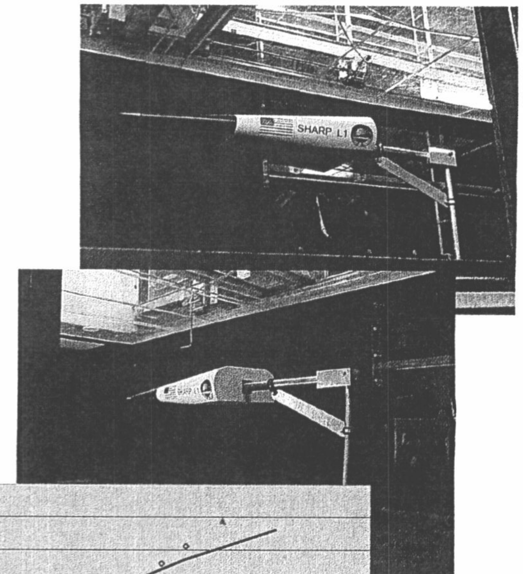


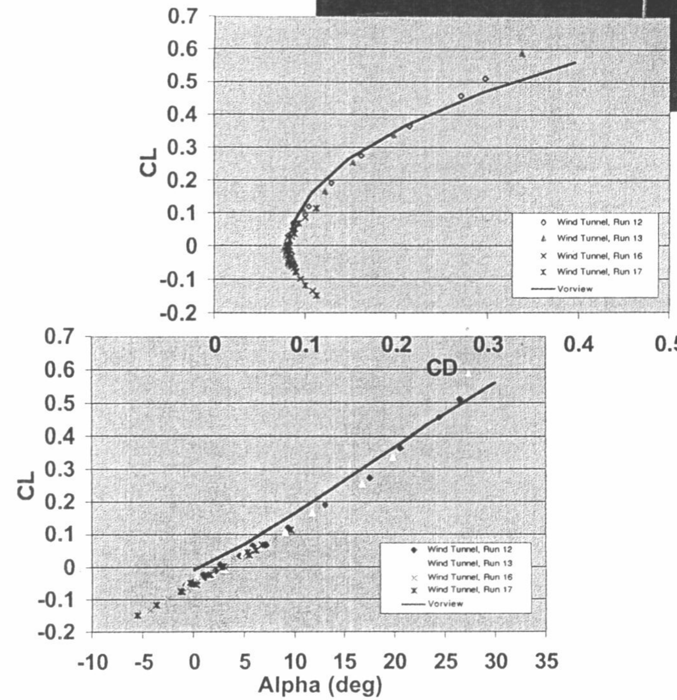
Navier-Stokes Solution
Mach 0.3, Alpha 10. Deg. Re = 60 mil.
Baldwin-Lomax Turbulence Model

Wind Tunnel

- Low Speed Wind Tunnel Testing Performed on L1 Vehicle
  - Data used to anchor codes to aid in development of CTV-V5
- Low Speed Model for CTV-v5 being fabricated







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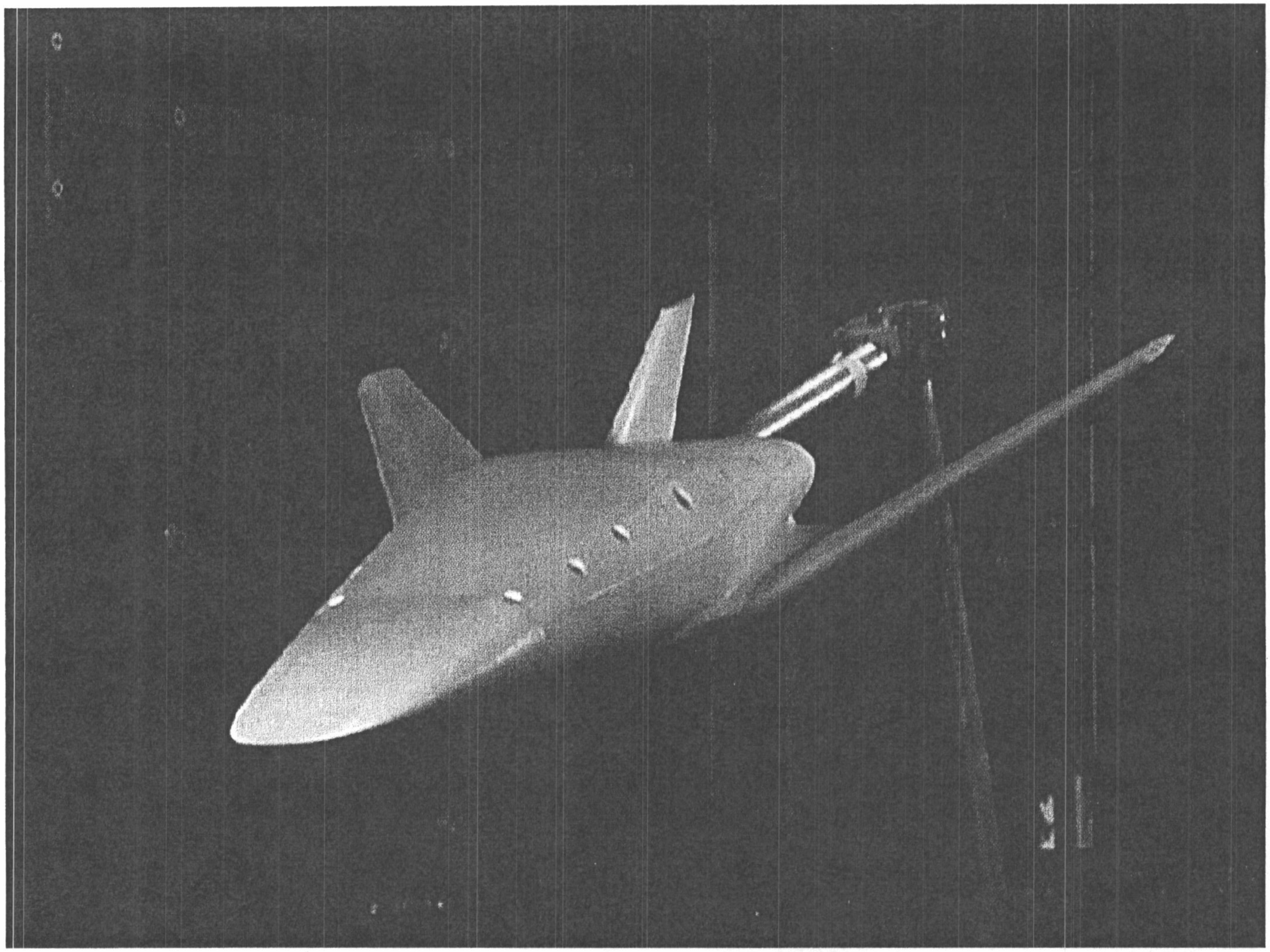
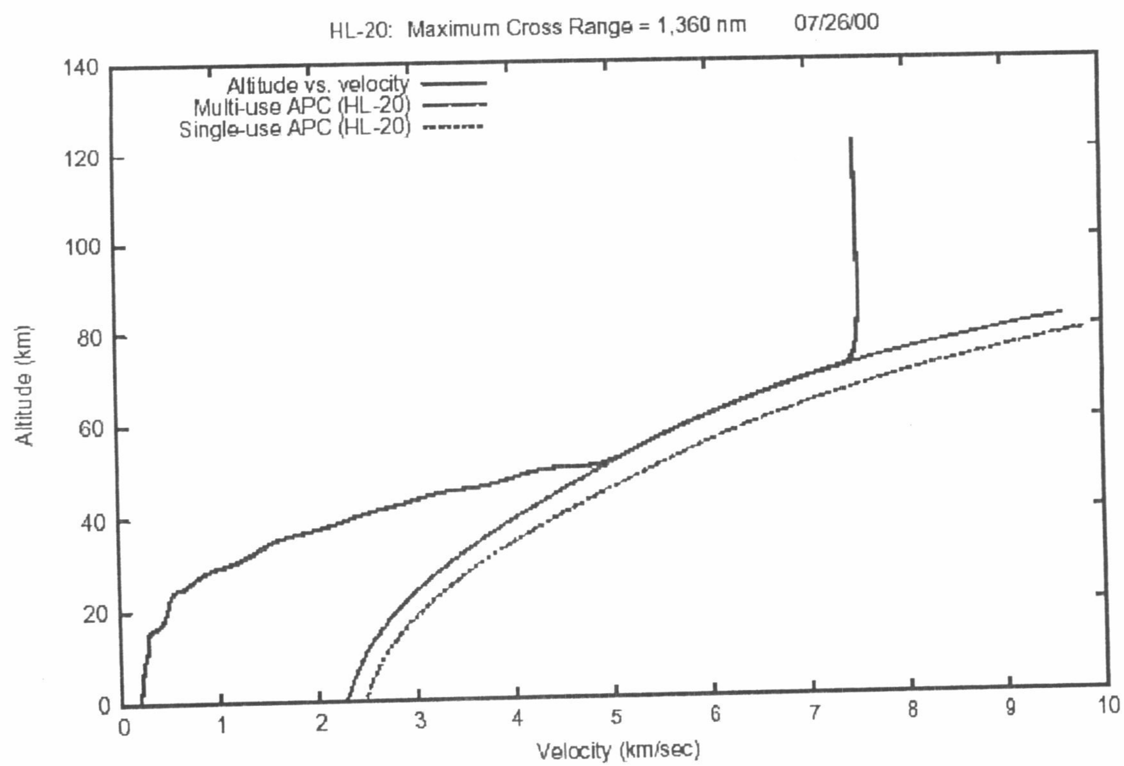
SHARP CTV, v5



APC: Aerothermal Performance Constraints

- Curve in (Velocity, Altitude) Space
- Drop Below => Too Fast / Too Low / Overheat



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Need to Generate Lift to Stay Above APC

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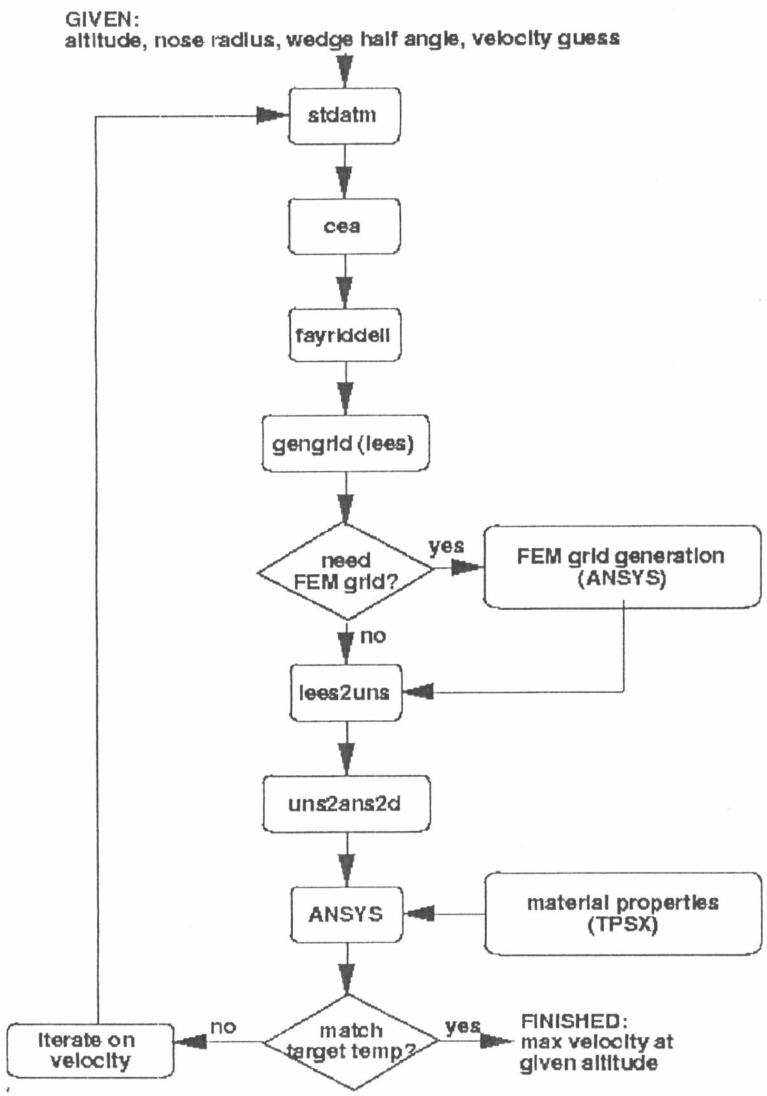
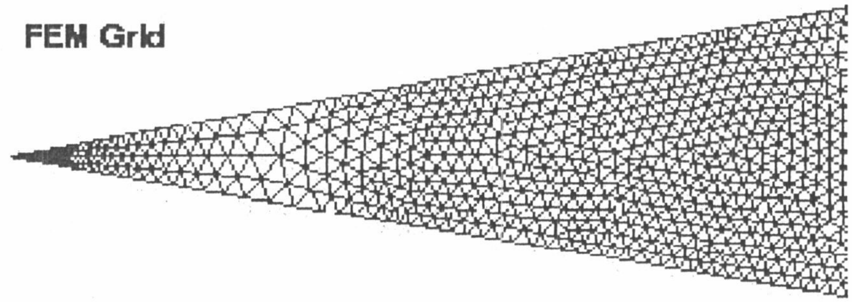
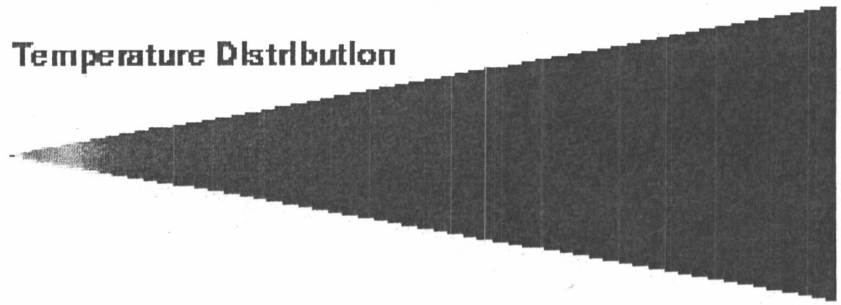
UHTC Aerothermal / Thermal Analysis
APC Development



FEM Grid



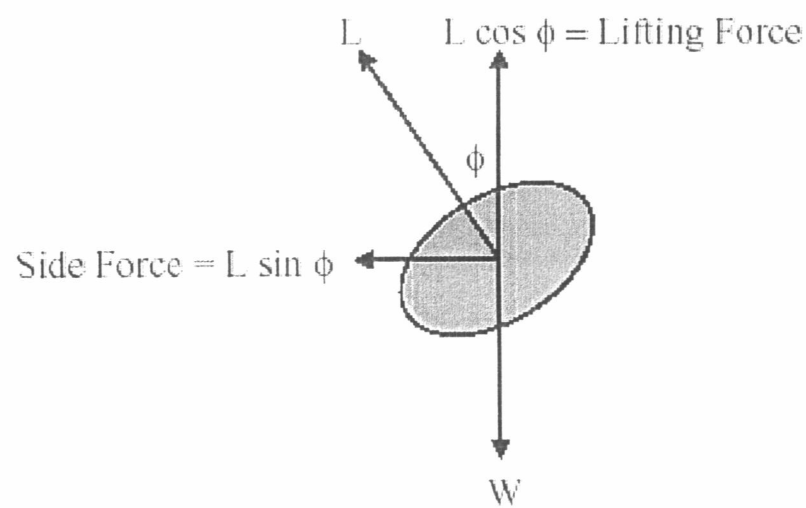
Temperature Distribution



Trajectory Optimization

NEED ENOUGH LIFT TO STAY ABOVE THE APC – NO MORE

- **Excess Lift Allows More Bank $\Rightarrow$ More Cross-range**
- **Excess Lift Allows Lower α $\Rightarrow$ Fly Closer to Best L/D**



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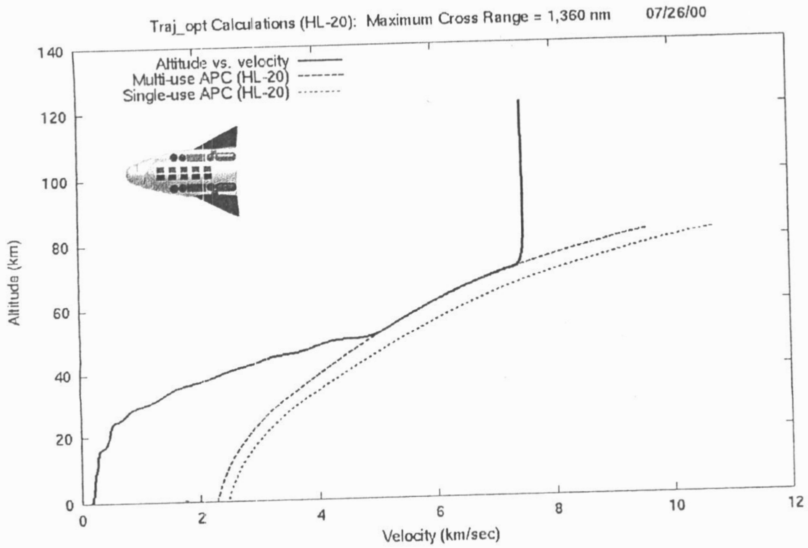
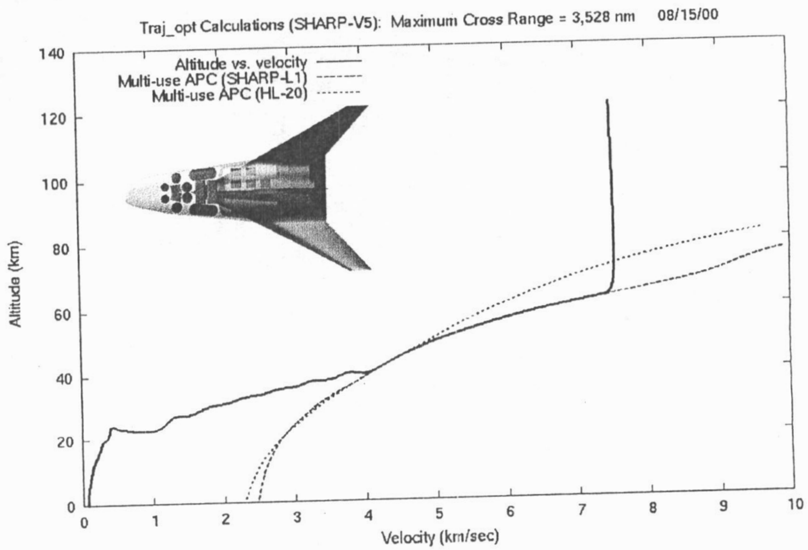
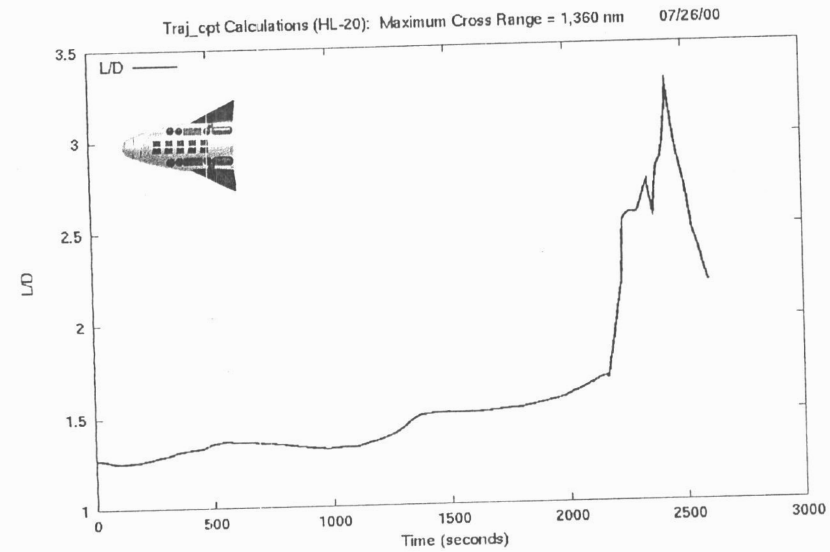
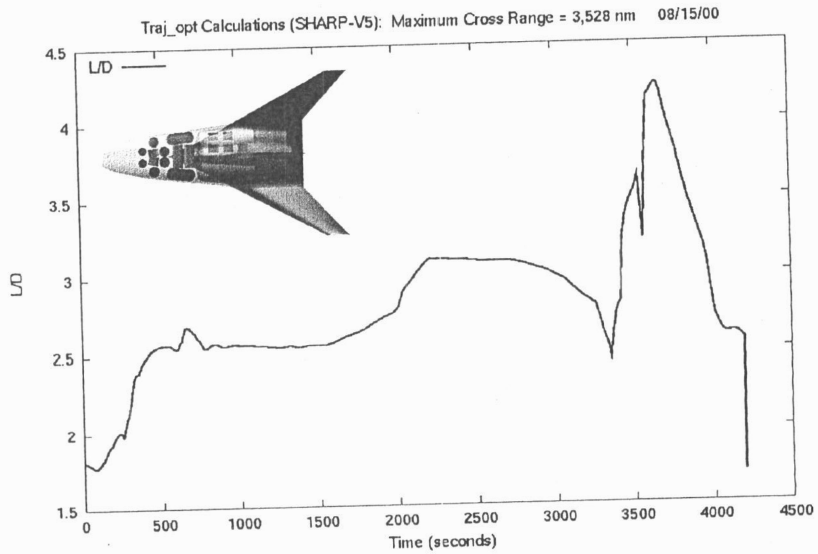
Max Cross-Range Trajectory Optimization









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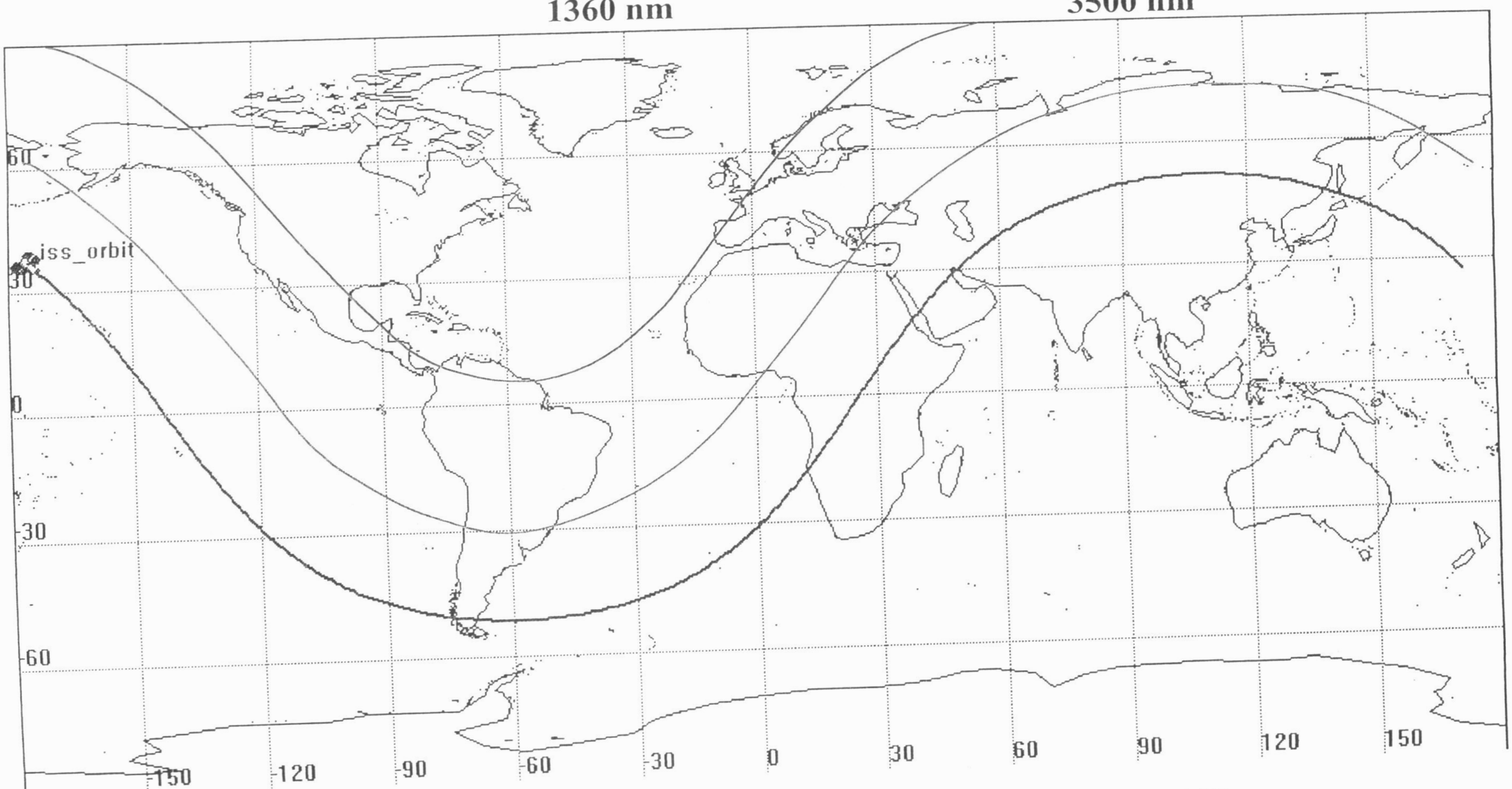
ISS Ground Track vs. Cross Range

— ISS Ground Track — HL-20 Max Cross-Range 1360 nm — Sharp-V5 Max Cross-Range 3500 nm



Significant Cross-Range advantages with SHARP-V5

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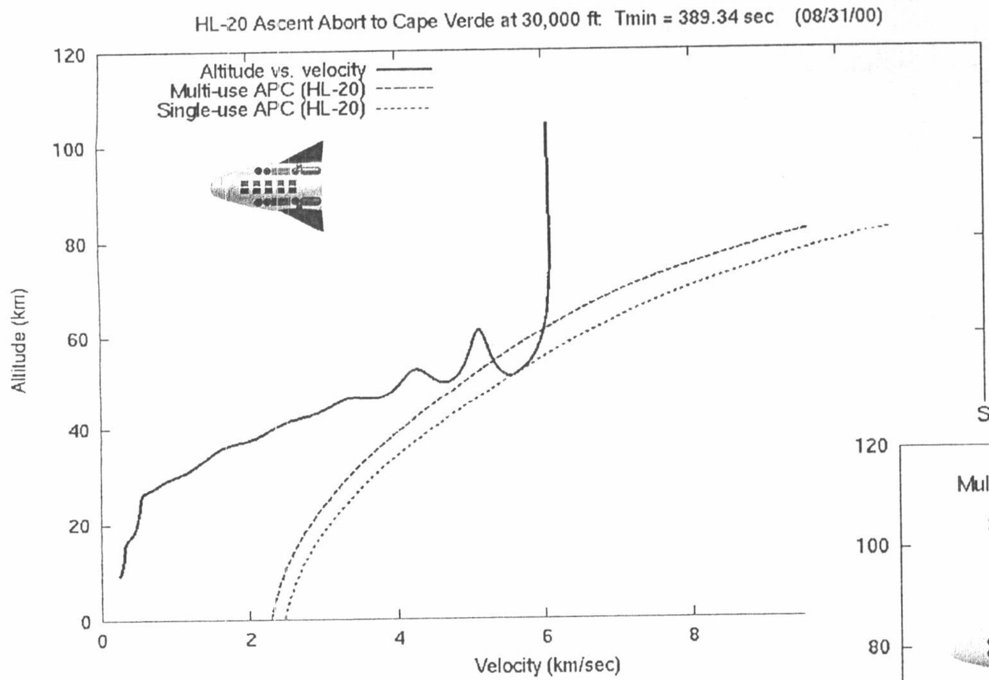
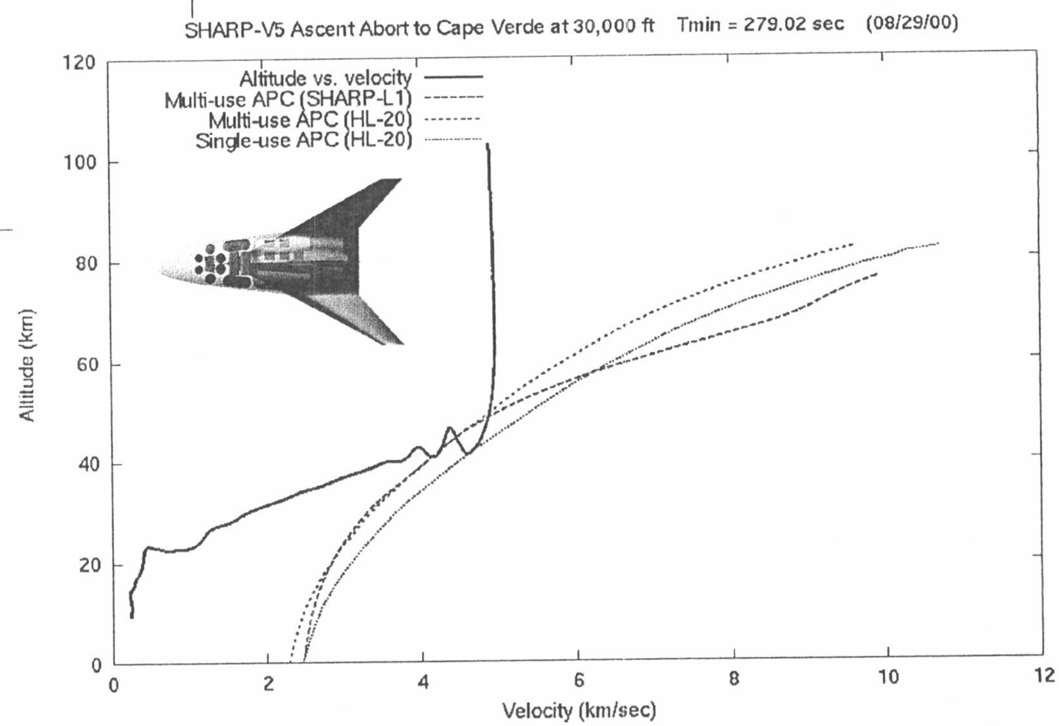
Ascent Abort Trajectories Optimization





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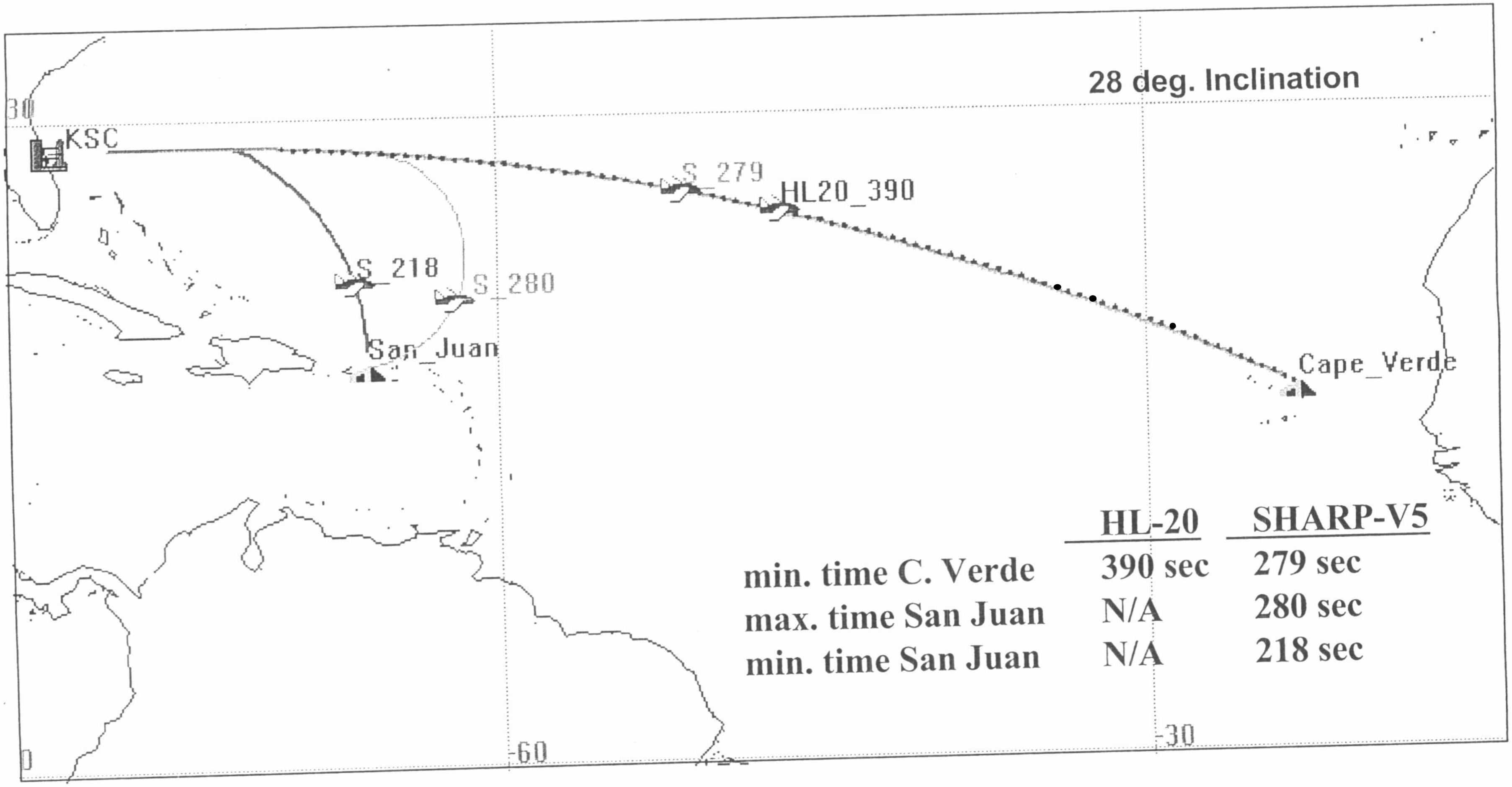
Abort Trajectories HL-20 and SHARP-V5



	HL-20	SHARP-V5
min. time C. Verde	390 sec	279 sec
max. time San Juan	N/A	280 sec
min. time San Juan	N/A	218 sec

Significant Abort advantages with SHARP-V5

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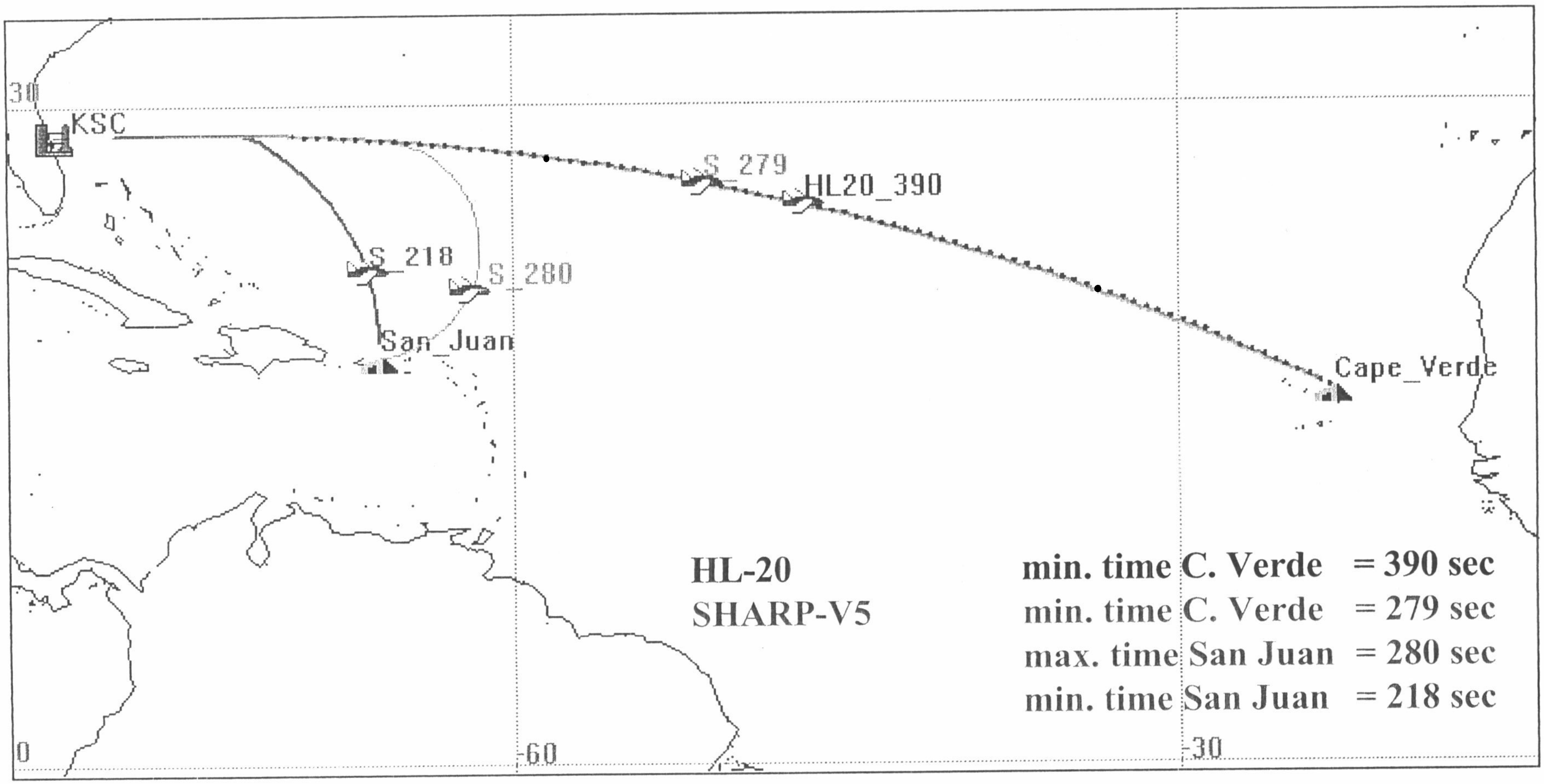
Abort Trajectories HL-20 and SHARP-V5

28 deg. Inclination



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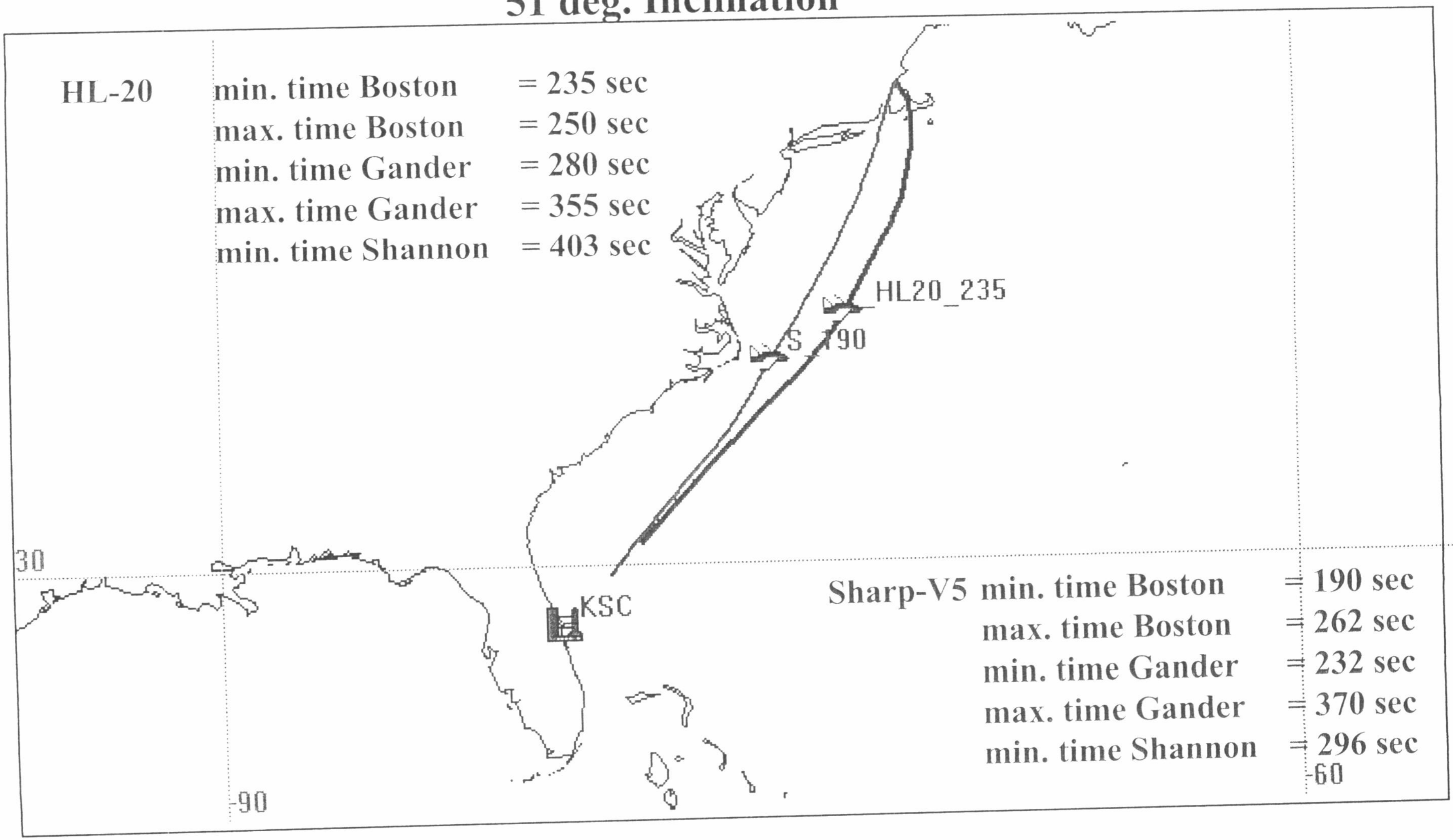
Abort Trajectories
HL-20 and SHARP-V5

51 deg. Inclination



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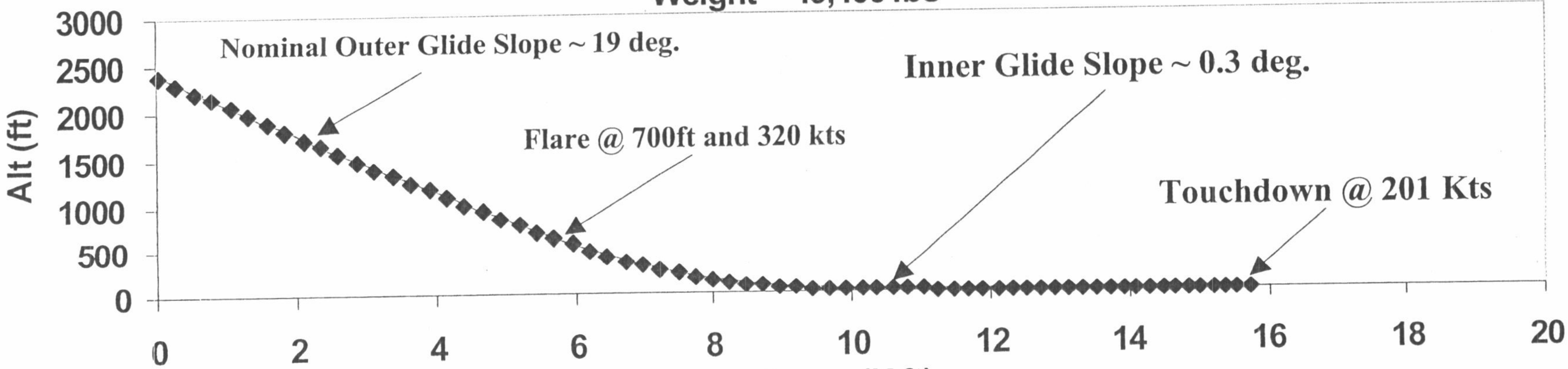
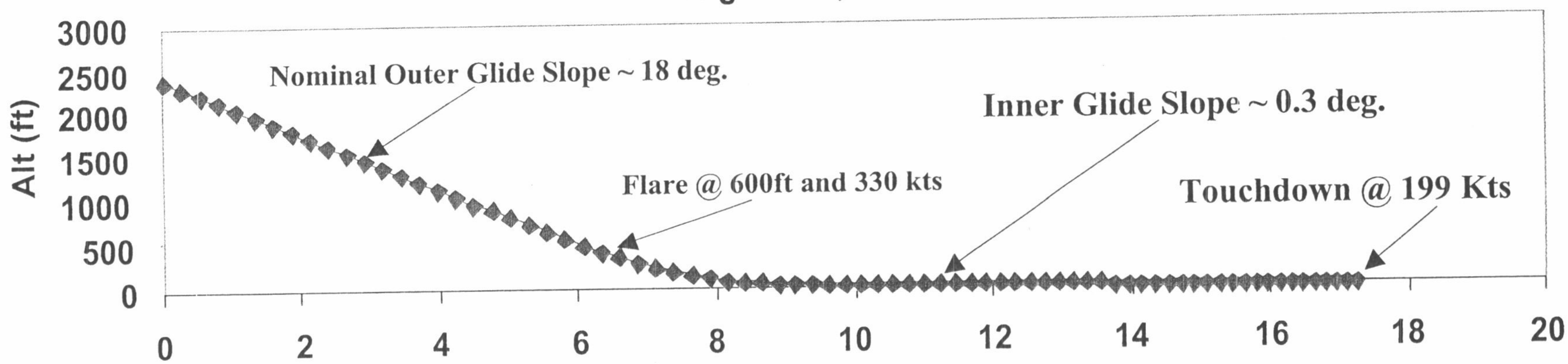
Landing Simulations

Nominal HL-20 Landing Flare Simulation
Weight = 19,100 lbs

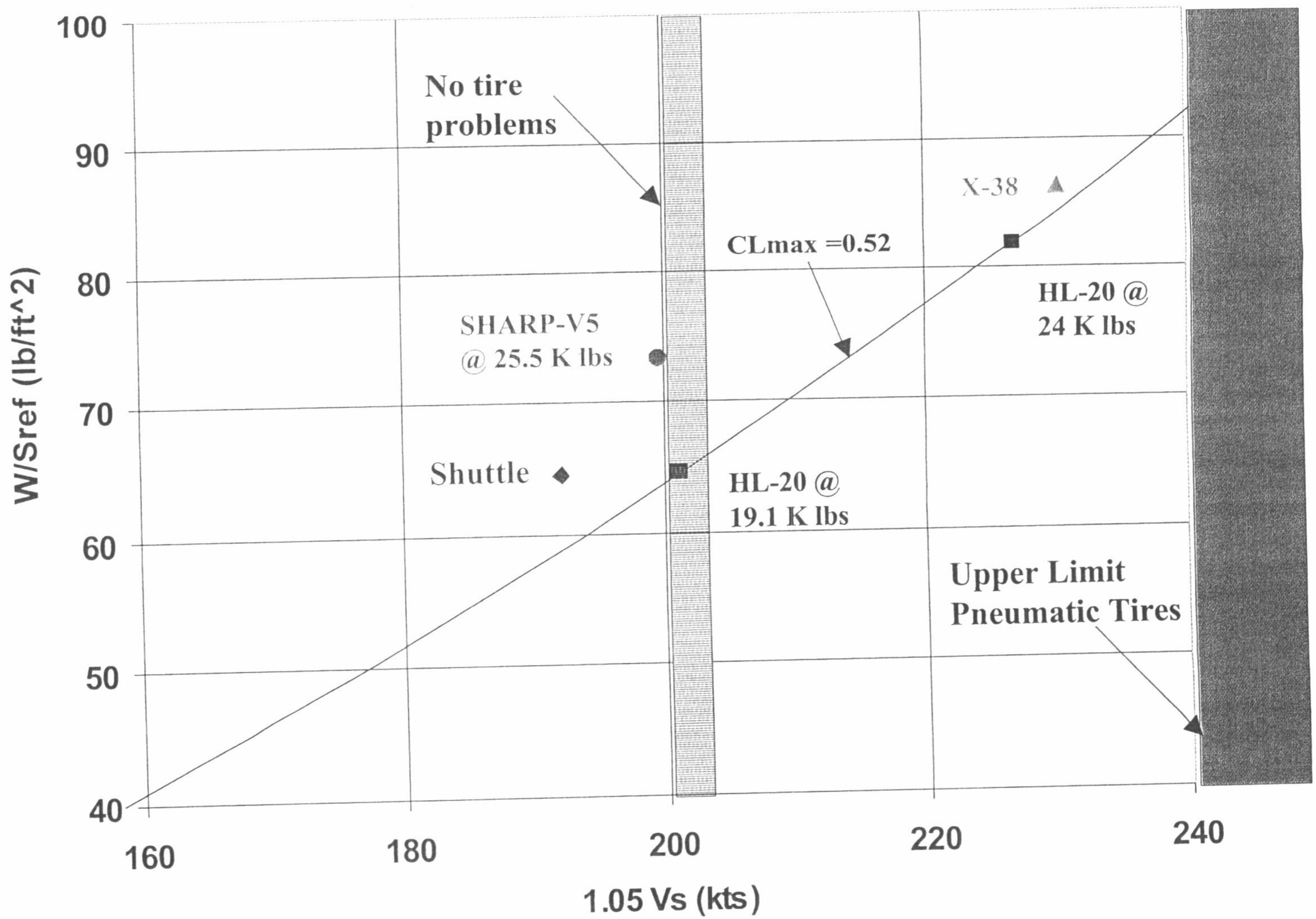


Nominal SHARP-V5 Landing Flare Simulation
Weight = 25,500 lbs



Landing Simulations

Wing Loading and CLmax Affects on Landing Speed



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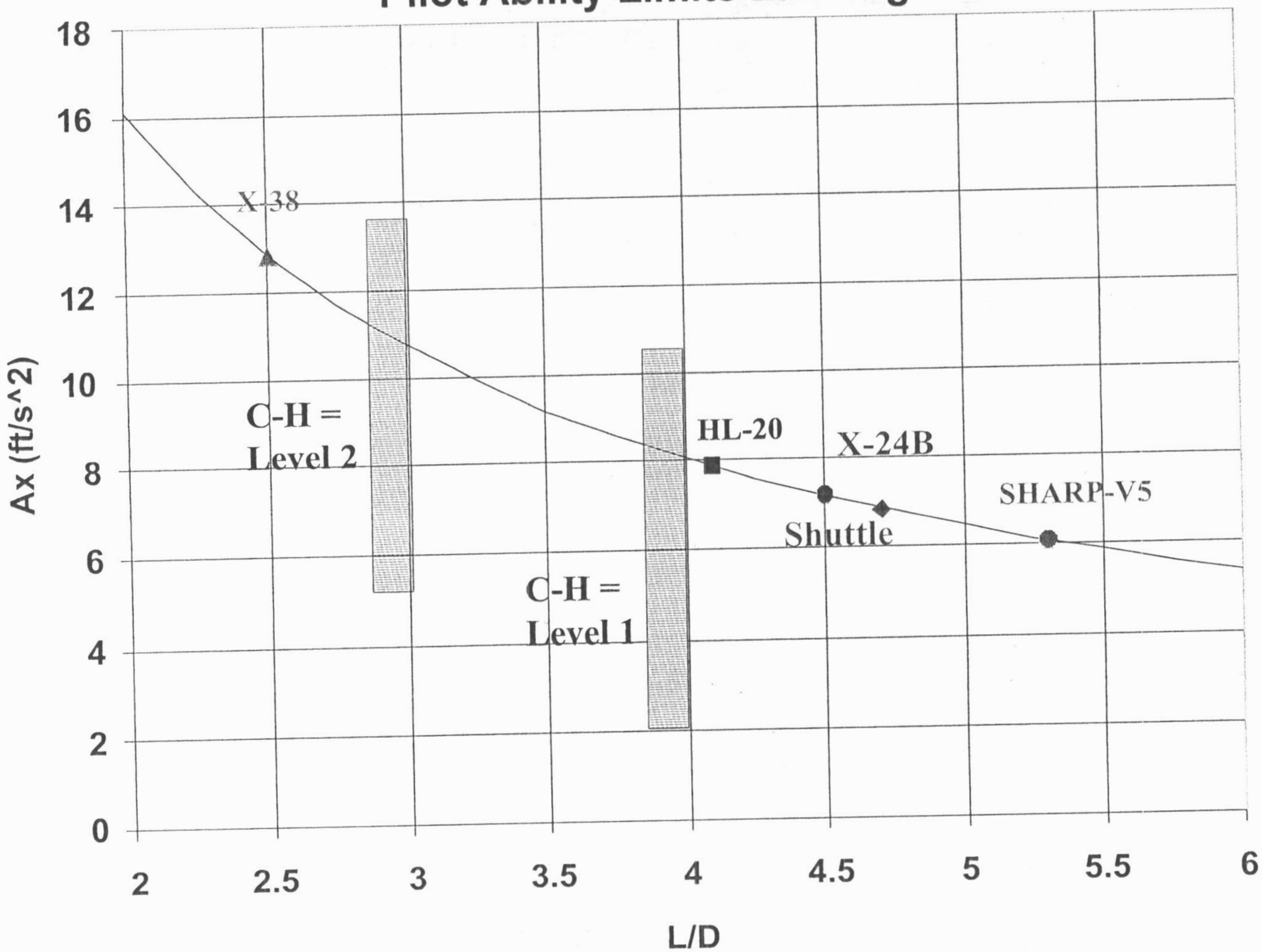
Landing Simulations

L/D Affects Landing Task Through Longitudinal Deceleration
Pilot Ability Limits Landing L/D



Significant Landing advantages with SHARP-V5

Summary of Ames Sharp CTV Architecture Study

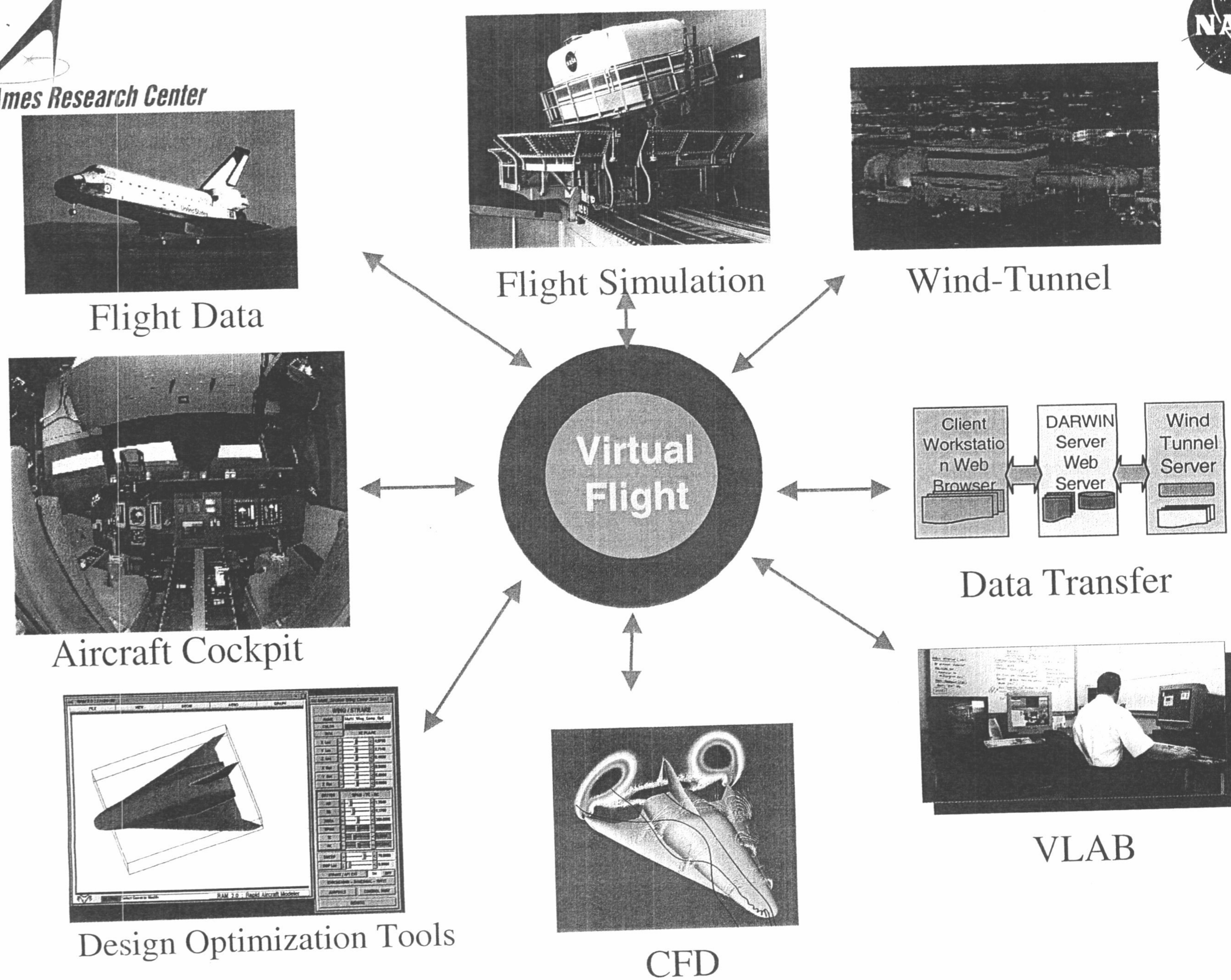
- Ames CTV study shows a viable closed vehicle for SHARP V-5:
  - Significant safety and performance benefits shown for a SHARP-V5 using UHTC's versus the HL-20 with Shuttle era materials
    - *Improved abort, cross range and landing capabilities*
  - Cross range benefits put larger heat load demand on acreage TPS - research warranted for thinner/lighter materials
- Results Published as AIAA Papers
  - Systems Analyis & Conceptual Design (AIAA 2001-2887)
  - Aerothermal Performance Constraints (AIAA 2001-2886)
  - Trajectory Analysis (AIAA 2001-2885)
  - Low Speed Aerodynamics & Landing (AIAA 2001-2888)

VF-RITE Introduction

Virtual Flight Rapid Integration Test Environment

Vision Statement:

Merge advanced Information Technologies to facilitate flight simulation as an integral part of the design process and return and employ the acquired knowledge base for the improvement of individual/total systems.


Flight Data
Flight Simulation
Wind-Tunnel
Aircraft Cockpit
Virtual Flight
Client Workstation Web Browser
DARWIN Server Web Server
Wind Tunnel Server
Data Transfer
Design Optimization Tools
CFD
VLAB

VF-RITE Goal and Objectives

Goal

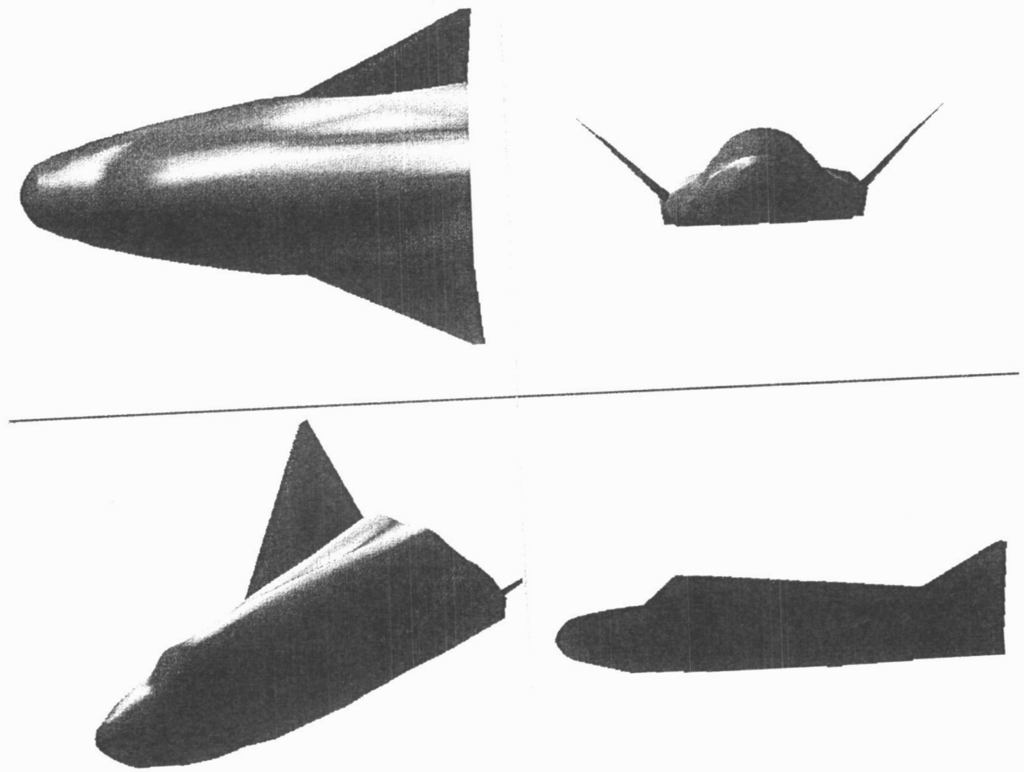
To develop and apply design and optimization tools, data generation methods, and real-time piloted simulation evaluations to a preliminary design case study: Sharp Crew Transfer Vehicle (CTV)

Objectives

- Develop rapid, iterative design process to be applied to a preliminary design for a re-entry space vehicle
- Meet all mission requirements for a CTV design
- Achieve optimal performance (aerodynamic, aerothermal, subsonic handling qualities, etc.) in all flight regimes
- Evaluate stability, control and handling qualities of Sharp CTV through real-time piloted simulations in NASA Ames Vertical Motion Simulator facility
- Apply return knowledge to design team to rapidly re-design CTV and obtain pilot evaluations on new design

VF-RITE Goal and Objectives (cont.)

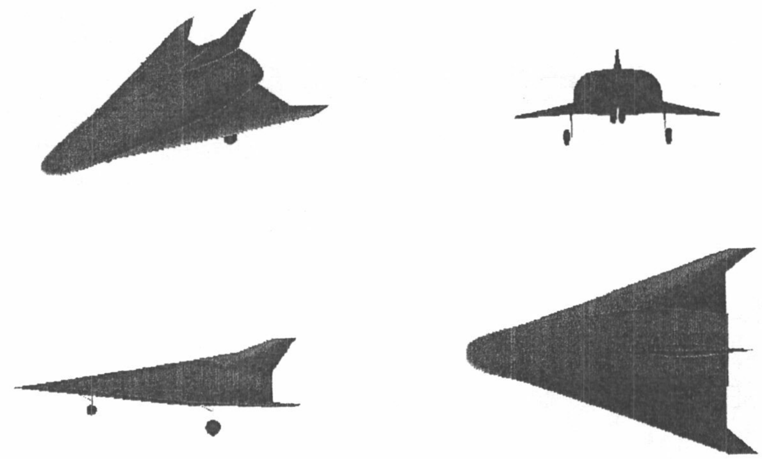
- Use HL-20 blunt-body design, developed by NASA Langley with same mission requirements, to validate methods and make comparisons



Crew Transfer Vehicle

Mission Requirements

- Reusable vehicle
- Launch on an expendable launch vehicle
- Accommodations for 8 passengers and crew
- Orbit-to-orbit transfer
- Rendezvous with Station
- Piloted and automated entry and runway landing capability



Design Constraints

- Use of Ultra High Temperature Ceramics (UHTCs) developed at NASA Ames to enable use of sharp leading edges
- Re-Entry weight less than 26000 lbs.
- Hypersonic L/D greater than 2
- Cross range capability greater than 2000 nm
- Subsonic L/D greater than 4

CTV-v7 or CV0

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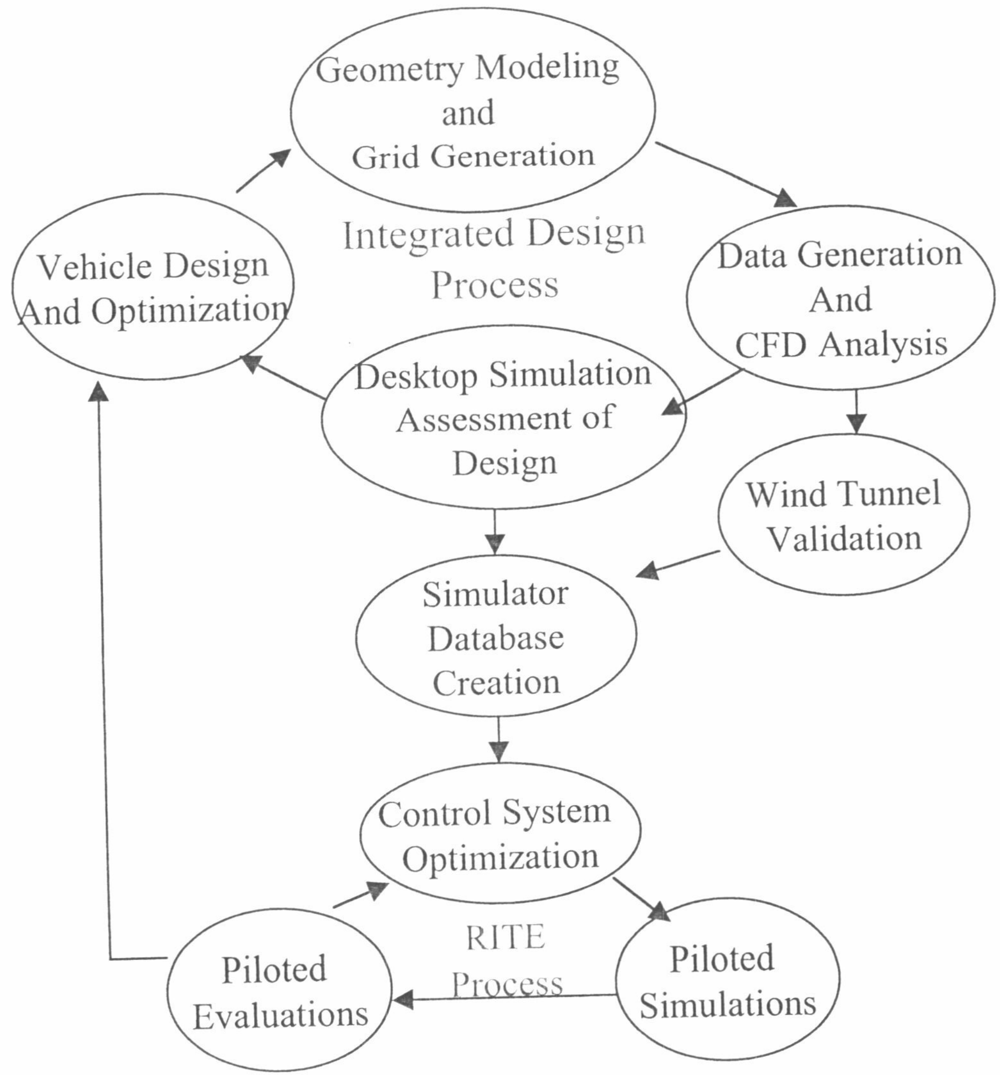
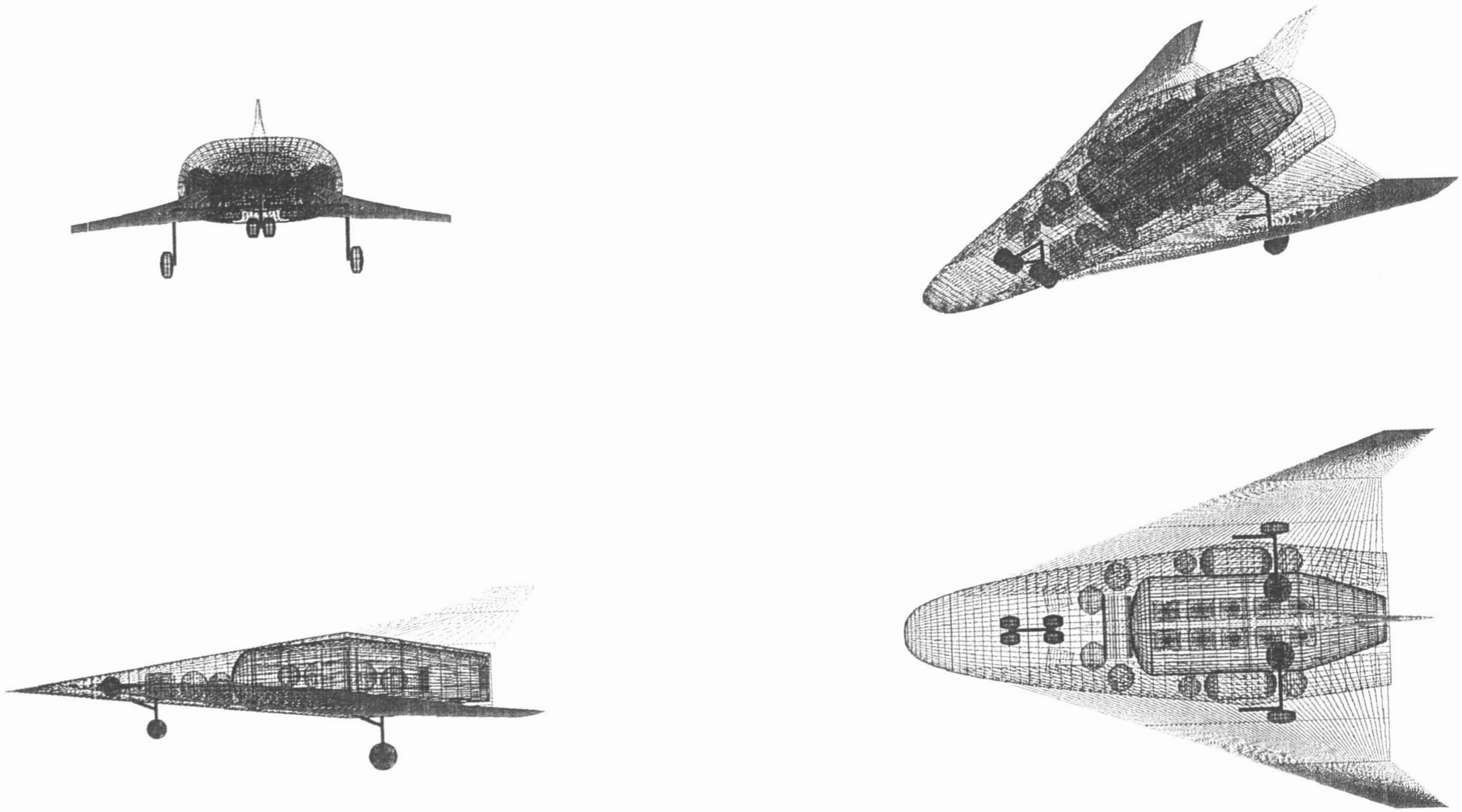
Integrated Design and RITE Process



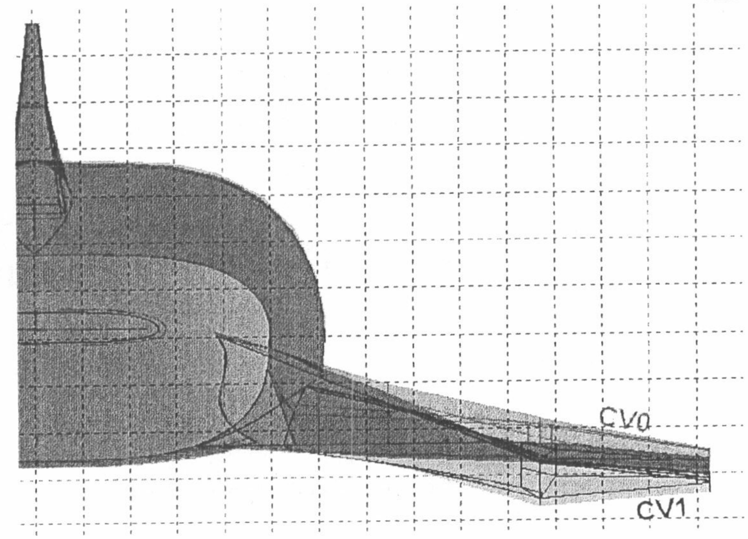
Vehicle Design and Optimization

- Aerodynamic shape optimization technique was developed by coupling:
  - AIRPLANE, an Euler unstructured-tetrahedral-grid-based CFD code
  - QNMDIF, an unconstrained quasi-Newton finite-difference optimization method
- Aerodynamic performance was optimized by varying selected geometry design variables
  - Wing leading and trailing edge twist
  - Wing dihedral
  - Camber
  - Elevator deflection angle
  - Fuselage geometry variables
- Manual design efforts were also used periodically
- Design objective
  - Trim at Mach 6.0 and alpha = 13°
  - Trim at Mach 0.3 and alpha = 9°
  - Achieve best L/D at 2 conditions simultaneously
- Ames CTV-v7 was used as baseline vehicle and renamed as Concept Vehicle 0 or CV0
- Subsequent configurations were named CV1 through CV5

SHARP CTV, v7

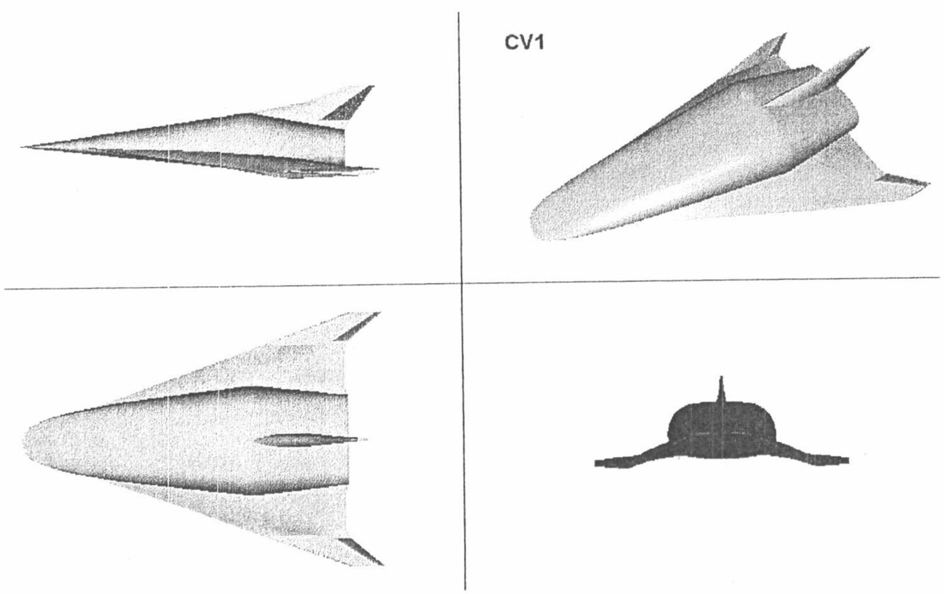


Concept Vehicle 1



Design Objective

- Modify longitudinal stability to improve trim conditions
- Simultaneously improve performance of vehicle at both design points



Design Variables

- Wing twist about trailing edge
- Camber
- Elevator (inboard wing flap)

Optimization Results

- Wing twist = -12.4°
- Elevator up = 0.05° for Mach 0.3
- Elevator down = 5.2° for Mach 6.0

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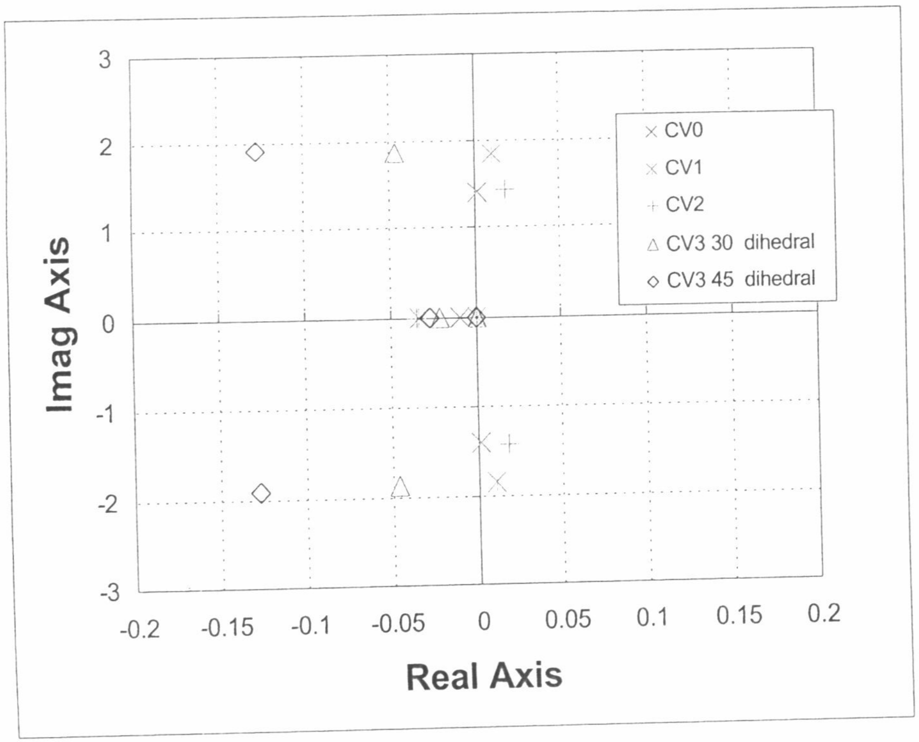
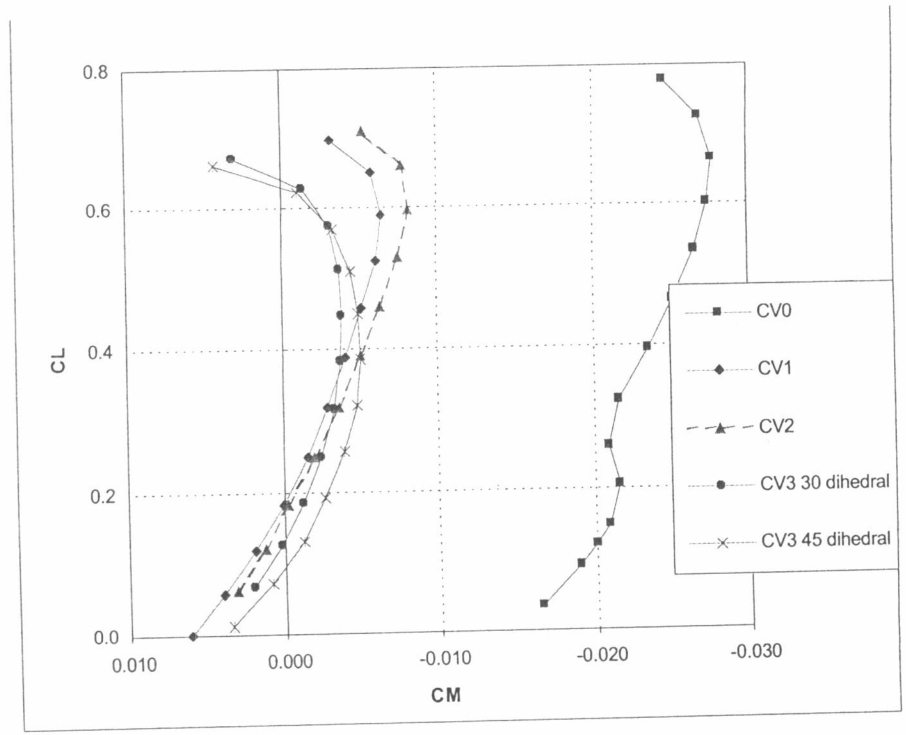
Concept Vehicle 3

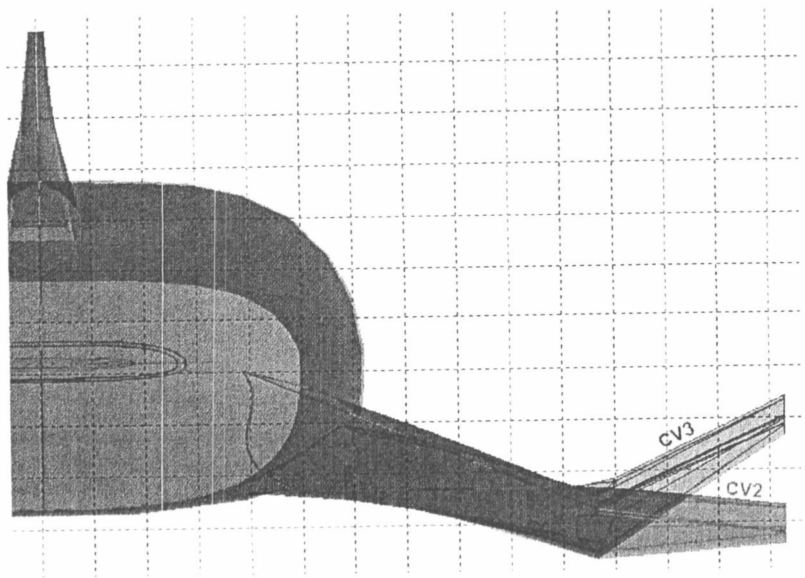
Design Objective

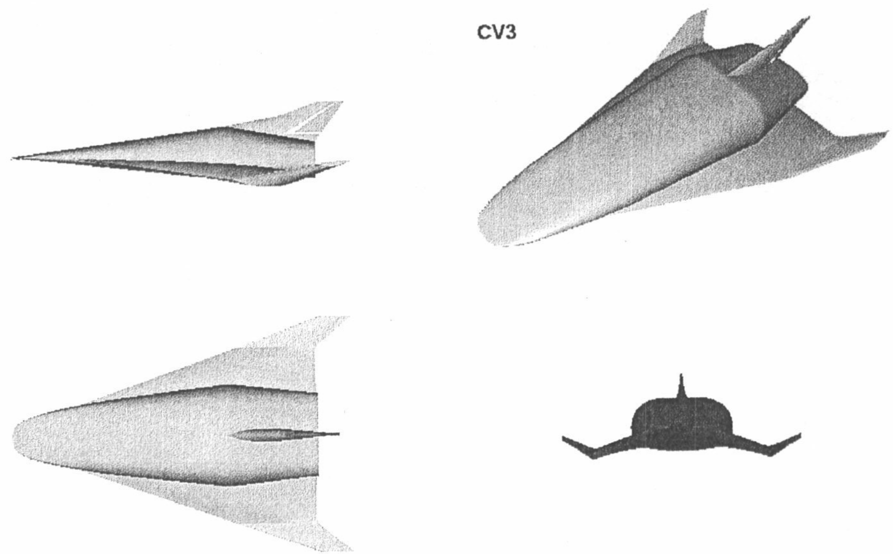
- Add wing dihedral to stabilize lateral-directional stability modes
- Simultaneously maintain or improve longitudinal stability





Concept Vehicle 3





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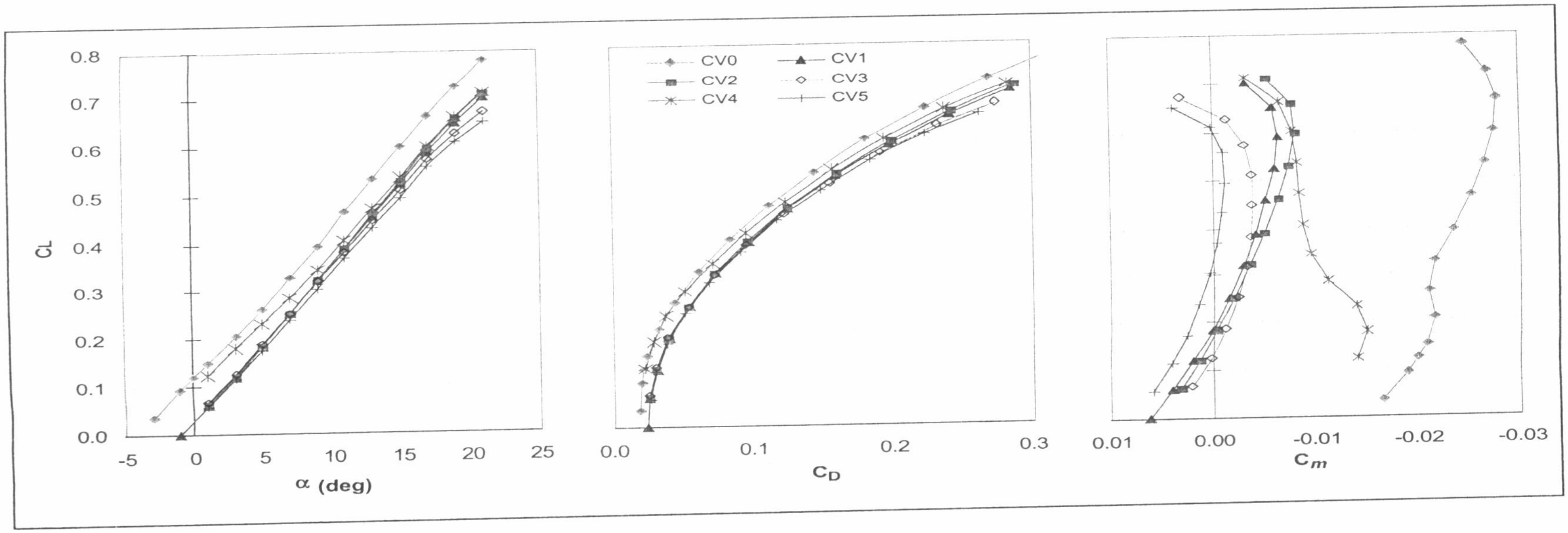
Mach 0.3 AIRPLANE Results



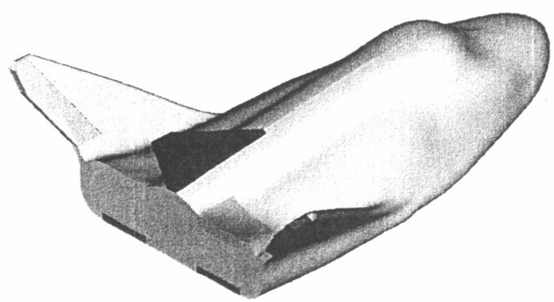
Low-Speed Wind-Tunnel Test

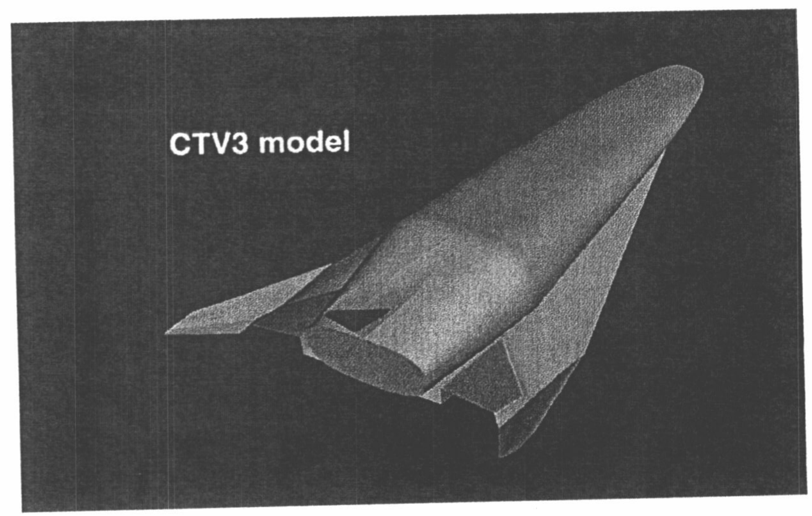
- Test conducted in NASA Ames Fluid Mechanics Lab 3-ft by 4-ft indraft wind tunnel
- Configurations tested: CV0 and CV2
- Models were fabricated using a stereo lithography technique for rapid delivery
- Moveable control surfaces
- 6-component force balance and 3-axis accelerometer used
- Data were taken at:
  - Mach number 0.11 and dynamic pressure 20 psf
  - Re 1.1 million based on body length of 22 in.
  - Angle of attack range was –3° to 22°
  - Sideslip range was 0 to 5°

Control System Design and Optimization

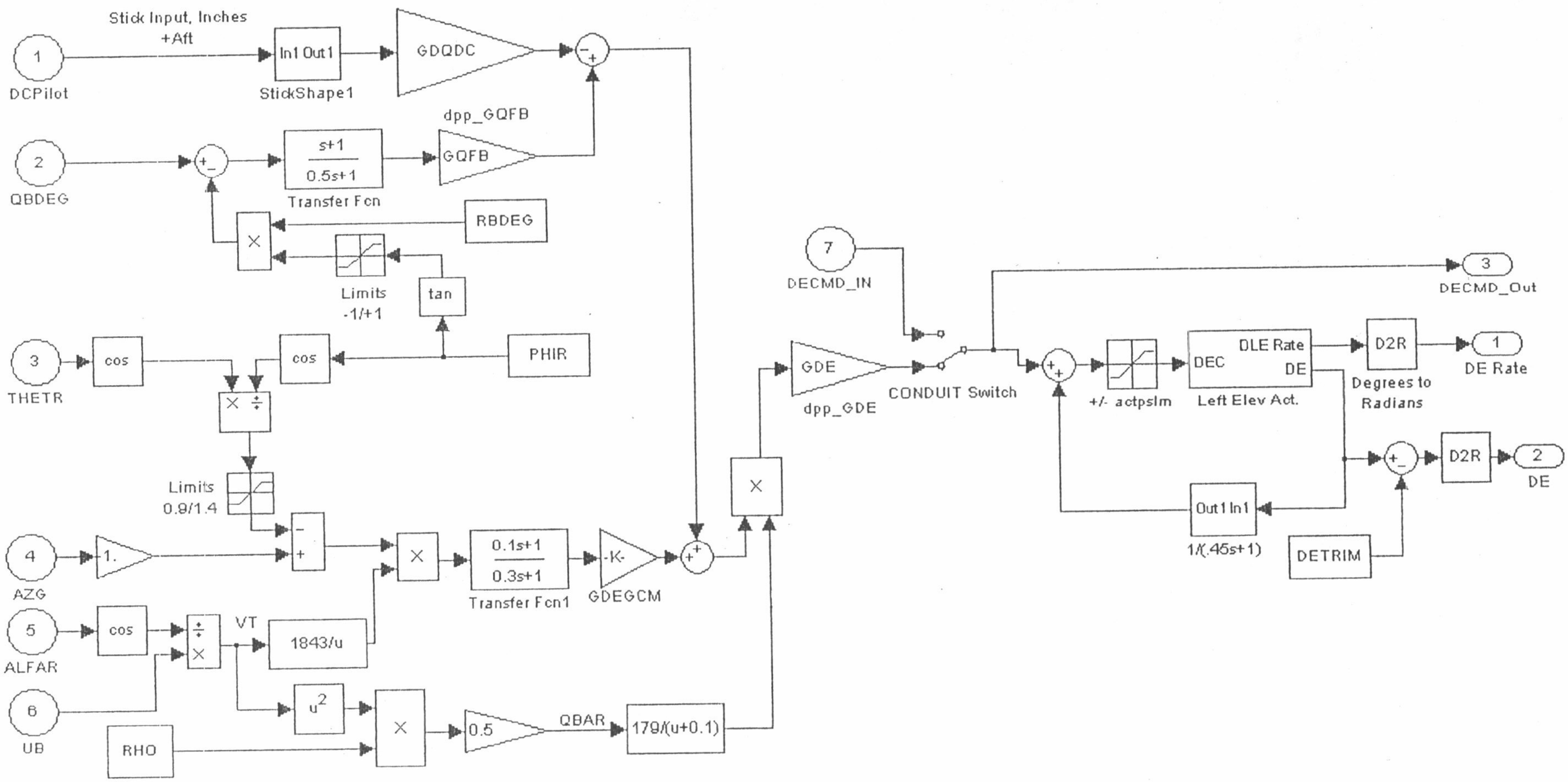
- HL-20 control system was used as starting point for CTV configuration
- Preliminary control system and lineaer aerodynamics model were developed
- Matlab and Simulink tools were used for development and initial evaluation
- Control system was modified to account for CTV control surfaces

HL20 model



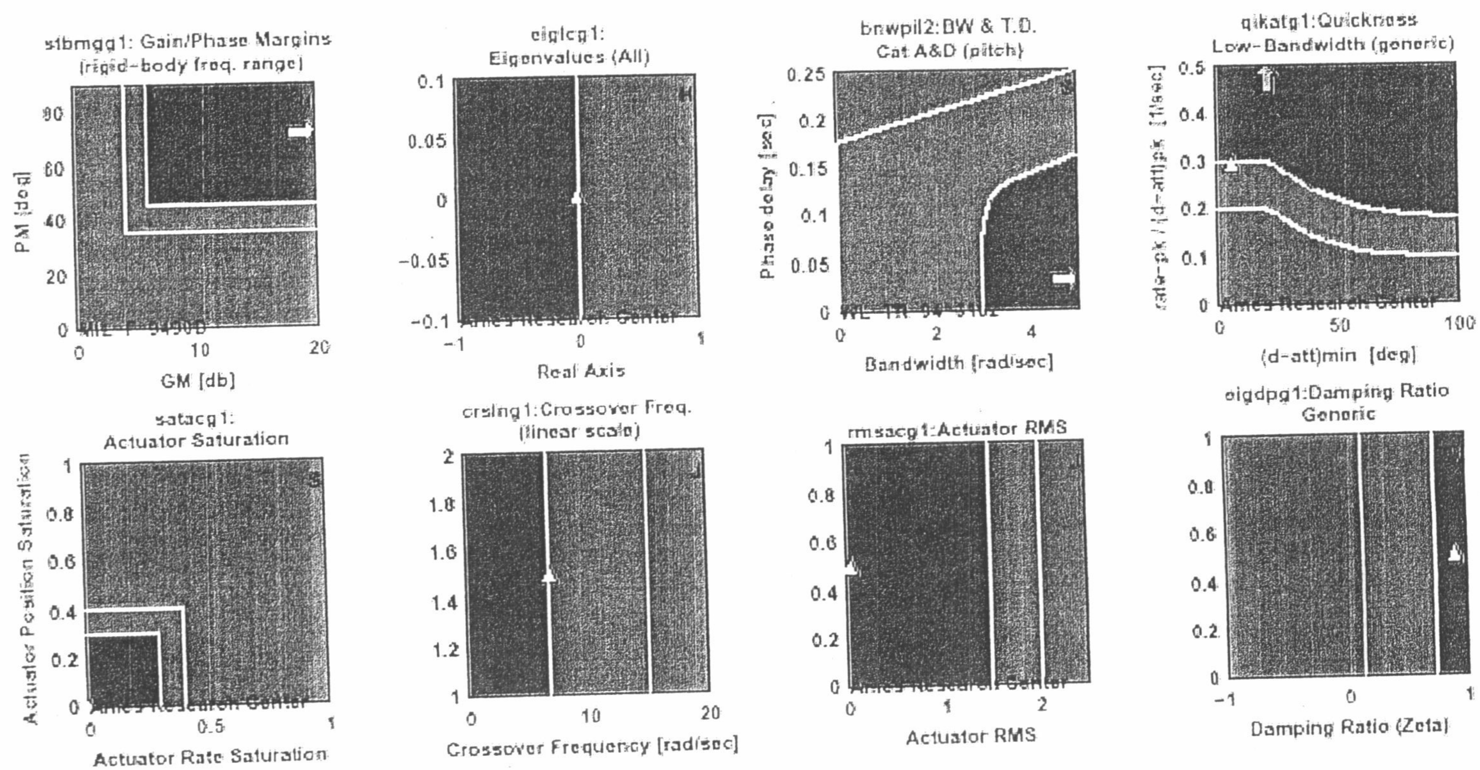


CTV Longitudinal Pitch Control Laws



Control System Optimization

- New control system gains were optimized for each new aerodynamics model using CONDUIT
- New longitudinal and lateral-directional specifications were defined to achieve Level 1 handling qualities



VMS Simulation Experiment

Objectives

- Evaluate HQs of SHARP CTVs for piloted tasks specified during approach and landing
- Use SSV simulation as baseline for comparison to SHARP CTV simulations
- Evaluate HQs for HL-20 simulation developed by NASA Langley for comparison to a blunt-body design with same mission requirements
- Evaluate HQs using Cooper-Harper ratings on 5 CTV configurations (CTV0 thru CTV4)
- Use pilot feedback and recommendations to re-design CTV for improved performance in handling qualities and/or aeroperformance
- Demonstrate capability to rapidly re-design configuration, re-generate aero model and obtain pilot evaluations on new design

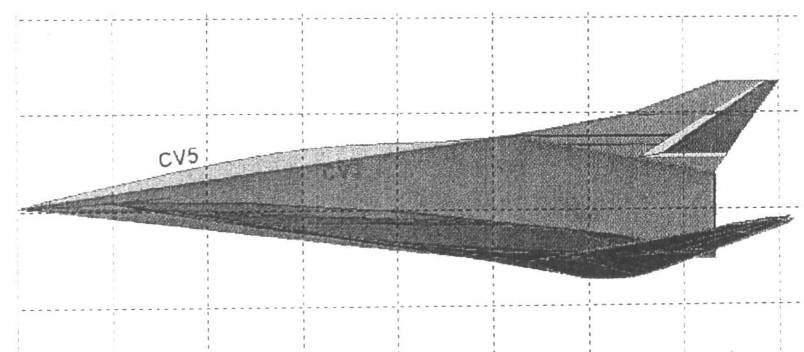
VMS Simulation Experiment

Piloted Tasks

- Nominal approach and landings
  - Initiated at 10K ft.
  - HUD display was used
  - Land within specified criteria
- Crosswind approach and landings
  - Realistic wind models with turbulence used
  - 15 kts. tailwind and 20 kts. crosswind
- Lateral offset landings
  - Approximate 400 ft. offset used
  - 300 ft. altitude return to centerline
  - Aggressive maneuver to excite lateral-directional modes

Rapid Redesign of CV5

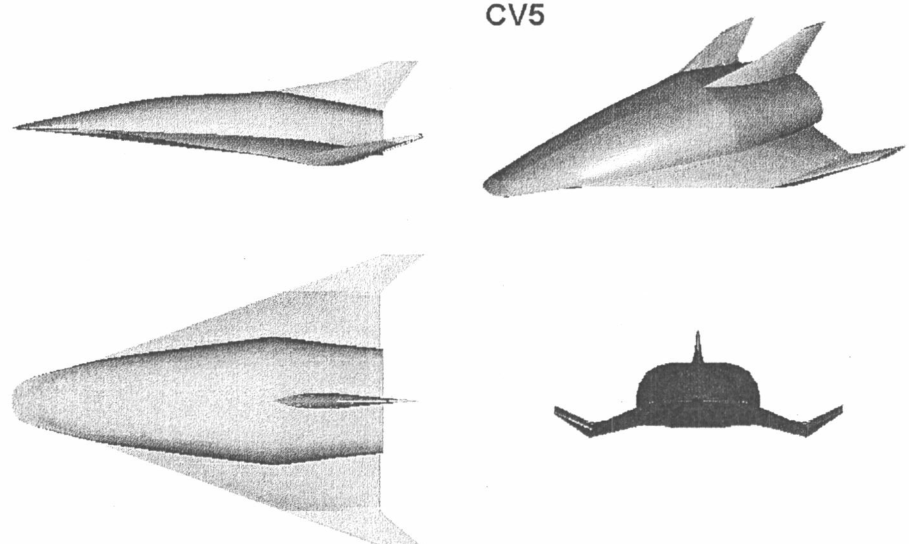
- From pilot feedback and recommendations, new aerodynamics model was generated and implemented into sim
- Fuselage geometry variables were optimized to increase fuselage width and nose droop to improve pilot visibility
- Seven design variables were used including:
  - Wing twist about leading edge
  - Body leading and trailing droop
  - Forebody camber
  - Forebody upper surface thickness
- Optimization results
  - Nose moved up by 1.2%
  - Aft body drooped by 3.2%
  - Wing twist was 2.29°
  - Forebody thickness increased at 25% and reduced at 60% of forebody



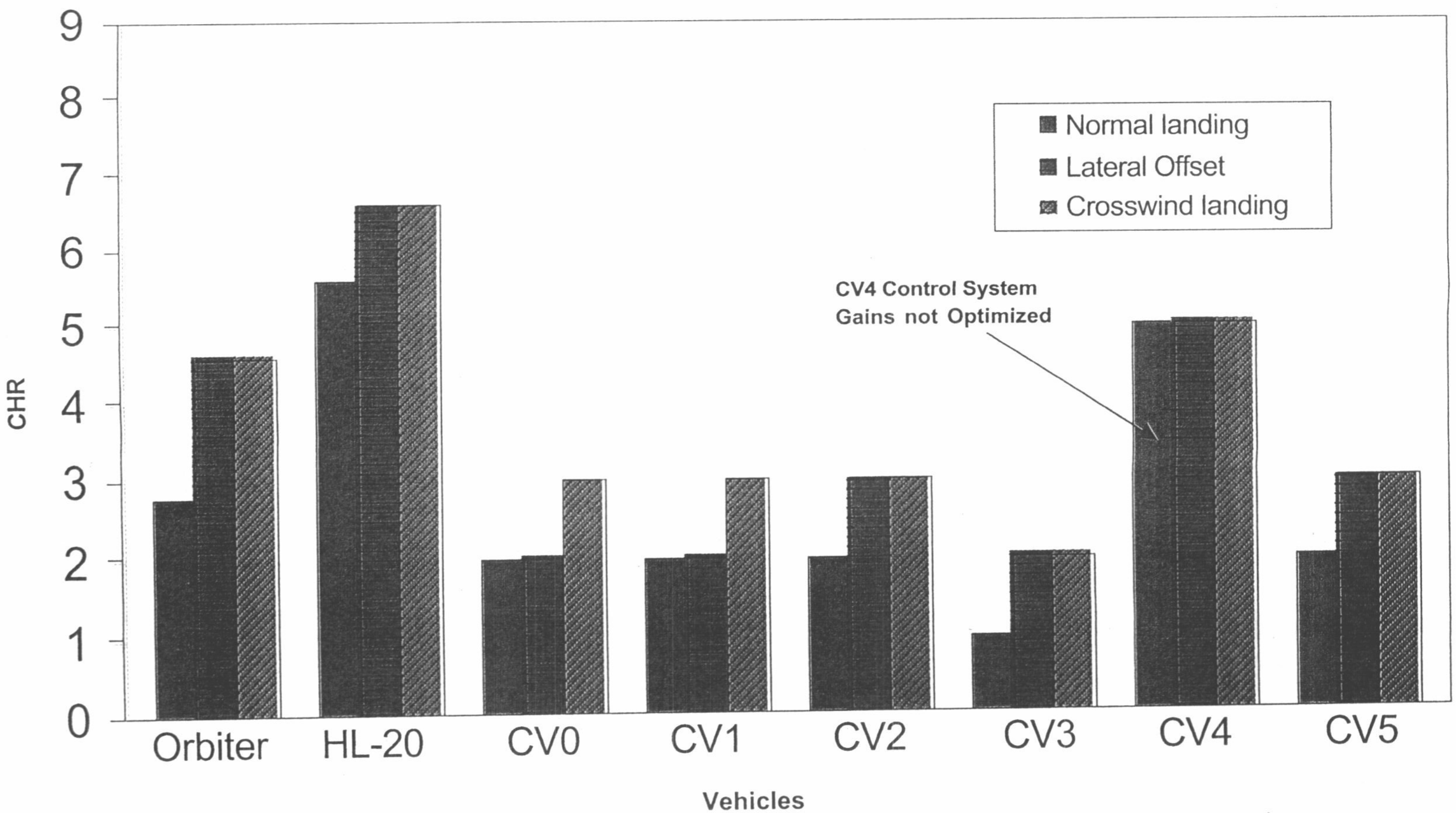
Rapid Redesign of CV5

- New computational simulations (Euler) were run
- New aerodynamics database for CV5 was generated
- New control system gains were optimized
- New pilot evaluations were obtained
- Rapid redesign process was completed within 4 weeks

CV5



Cooper-Harper Ratings



Summary of VF-RITE Task on Sharp CTV

- Virtual Flight RITE project demonstrated capability to integrate CFD, flight and wind-tunnel data into a simulation
- Design of a Sharp Crew Transfer Vehicle concept was developed using integrated design process
- Aerodynamic models for 6 CTV configurations (CV0 through CV5) were developed
- Low-speed wind-tunnel test was conducted to validate CFD results
- Simulation experiment was conducted to evaluate low-speed handling qualities in approach and landing phase
- Control system optimization technique was developed for rapid optimization of control system gains
- Six astronaut pilots evaluated each configuration using Cooper-Harper ratings
- Using pilot feedback, a new configuration was developed and cycled back through the simulation evaluation
- AIAA 2002-4881

Conclusions & Future Work

- A Closed SHARP Class CTV has been presented which shows
  - Improved re-entry performance compared to blunt vehicle concepts
  - Improved Ascent Abort Safety compared to blunt vehicle concepts
  - Similar Landing Performance to blunt vehicle concepts
- A Better Understanding of SHARP Class Vehicles has been Established
  - Drivers for Using UHTC are Established
  - Understanding of drivers for UHTC APC's
- There remains the need to perform a continued and more in depth study
  - Structure & UHTC TPS Integration
  - Cost , Operations, Safety & Reliability
  - RTLS, ATO, Landing Performance, Ascent Stack Stability ….
- NASA and Industry has shown great interest on continued work
  - 2nd Gen Leader/Follower Concepts and 2nd Gen NRA